Vitalized FUNDAMENTALS of ELECTRICITY

(in Graphicolor)

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VITALIZED FUNDAMENTALS OF ELECTRICITY

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PREFACE

PURPOSE OF THIS BOOK

This book follows the pre-induction training course, *Fundamentals of Electricity,* as outlined in the War Department manual PIT-101 and recommended to the high schools by the U. S. Office of Education.

As explained in the introduction to that manual, the course is designed for those students (about 80% of the boys) who will enter the armed forces immediately upon graduation. In view of this purpose there is a clear need for a compact book which the student can use, first as an aid to his classroom study, and later as a convenient, reliable handbook for reference and review at all times.

Vitalized Fundamentals of Electricity is such a book. It is not intended to replace the comprehensive texts which have already been published for the course. Low in cost, small in size, it is intended to be the student's permanent guide, clarifying and fixing the essential ideas of the subject, and standing by whenever a memory refresher may be needed.

The following paragraphs will point out the special features and unusual devices of this book which make it ideally suited to the purposes just outlined.

TWO-COLOR (*GRAPHICOLOR*) PRESENTATION

The Diagrams. What the experienced teacher does with colored chalk at the blackboard has here been done with two-color printing. In each diagram, those parts which illustrate or explain the basic idea are highlighted and distinguished from other necessary but less important details by means of color. As a result, the diagram is more easily understood, more permanently retained in the mind, more attractive and interesting than an ordinary black-and-white illustration.

Since the purpose is to teach underlying principles, not structural intricacies of electrical devices, each diagram is simplified —each has been carefully planned and carefully executed to present a maximum of useful information without confusing, irrelevant detail.

The Text. The second color has been used to spotlight important formulas in the text; it is also employed to indicate important steps in the *Typical Problems.*

SELECTION OF CONTENT

Within the general outline of subject content delineated by the PIT manual, emphasis has been placed on those topics and those illustrative applications which contribute to the main objective —providing basic knowledge for the boy who will soon be operating the machines and electrical devices of modern warfare. Each paragraph and each diagram in this book have been tested against that criterion.

Some portions of this book have been adapted from *Vitalized Physics,* a concise text by the same author. Both the organization and content of those sections have been checked and modified to meet the PIT outline requirements.

VALUABLE OPTIONAL TOPICS

Since many of the students will continue with advanced study of radio and its applications (either in school or in the services), the concluding chapters of the book have been added to provide a groundwork for such specialization. These chapters on alternating current theory, sound and wave phenomena, and radio fundamentals are simply written and well-illustrated. A discussion of vectors, in the Appendix, supplements the treatment of alternating current theory.

OBJECTIVE QUESTIONS AND PROBLEMS

Abundant questions and problems at the end of each chapter test understanding of principles as well as factual knowledge acquired. Answers (in red) are given for all problems; these answers, computed with a slide rule, are accurate to 3 significant figures.

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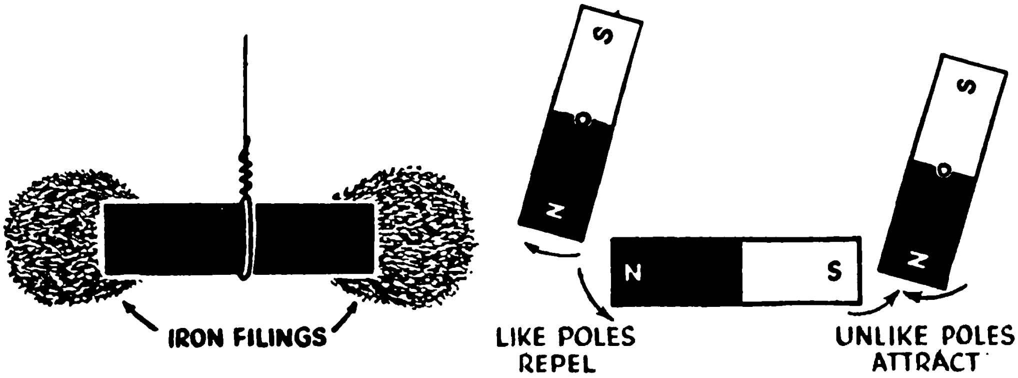
ONE— MAGNETISM

Magnets and Magnetic Materials. Some 2000 years ago, it was found that the mineral *magnetite,* or *lodestone* (now known to be an oxide of iron, Fe_3O_4), has the ability to attract small pieces of iron. This force of attraction is called *magnetism,* and any object or device which exerts magnetic force is called a *magnet.* Magnetite is a *natural* magnet. Man-made magnets are called *artificial* magnets. These are generally composed of an alloy steel (mostly iron), and may assume various shapes. Magnetism is also produced whenever an electric current flows through a wire. Usually the wire is wound in the form of a coil around a soft iron *core.* Such a device is termed an *electromagnet.*

Iron and its alloys are not the only materials attracted by a magnet, although, for practical purposes, they are virtually the only ones used. Other magnetic materials include nickel, cobalt, liquid oxygen, certain alloys such as Alnico (composed of aluminum, nickel, and cobalt), and a few others. *Non-magnetic* materials are exemplified by copper, brass, tin, glass, water, etc.

Magnetic Polarity. An ordinary bar magnet dipped into iron filings will collect them at its ends, but not at its center. Such spots where magnetic attraction is most pronounced are called



The iron filings indicate that the magnetic field is strongest at the ends (poles) of a magnet. Like poles repel and unlike poles attract.

poles. So far as is known, a magnet must have at least two poles.

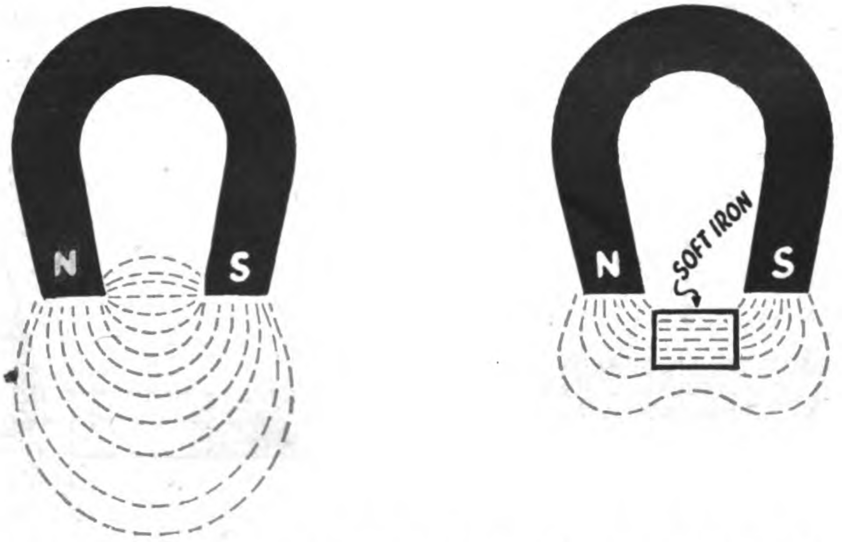
If a long bar magnet is suspended or supported so that it rests horizontally and can swing freely, it will be found to come to rest pointing approximately north and south. The end pointing to the north is called the *north-seeking pole,* or simply, the *north pole.* The other end is the *south-seeking* or *south pole.*

If another magnet is brought near the suspended magnet, it will be found that the two north poles, or the two south poles, repel each other, whereas the north pole of one and the south pole of the other attract each other. Thus we have the *law of magnetic force: like magnetic poles repel each other; unlike magnetic poles attract each other.*

Magnetic Fields. Every magnet is surrounded by a space where its magnetic effects are present. This is called the *magnetic field.* Every magnetic field is said to contain magnetic *lines of force,* or lines of *magnetic flux.* These are lines drawn in the magnetic field so as to show at every point the direction in which a small compass would point. Magnetic lines of force have very definite and important properties.

1. *Lines of force never cross one another.* At a given point in the field, a compass can point in only one direction.

2. *Lines of force form closed curves.* By agreement, magnetic lines of force are considered to run from the north pole around



Soft iron is much more permeable than air; hence the magnetic lines of force are concentrated in the iron.

to the south pole of the magnet, and to complete their path through the magnet itself. However, nothing *flows* along the lines of a magnetic field.

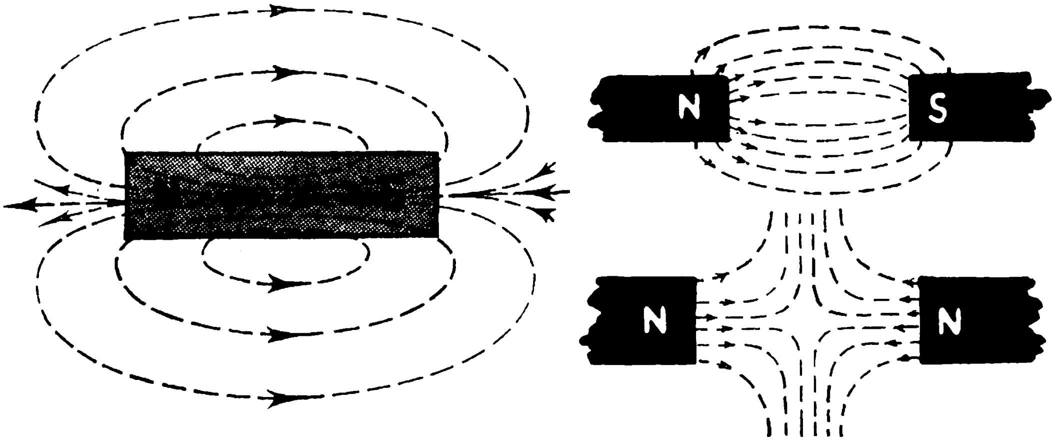
3. *The concentration of the lines of force indicates the strength of the magnetic field.* That is, the number of lines perpendicular to a unit area of the field is a measure of field strength.

4. *Lines of force follow the path of least resistance.* Magnetic lines of force pass more readily through a piece of iron placed between the poles of a magnet than they do through air. The ability of a substance to concentrate magnetic lines of force is called its *permeability.* Iron is much more permeable than air. All materials are permeable to some extent. *Permalloy,* an alloy of iron and nickel, has extremely high permeability.

Typical Magnetic Fields. 1. *Around a bar magnet.* The lines of force about a bar magnet leave the north pole and enter the south pole. They are crowded together at the poles but there are relatively few lines outside the center of the bar.

2. *Between unlike poles.* The lines of force between two unlike poles connect the poles and are most concentrated in the space between them. The lines of force tend to draw the poles together.

3. *Between like poles.* The lines of force between two like poles change their direction abruptly. A line originating at one pole does not terminate at the other. The repelling lines of force tend to keep the two unlike poles apart.

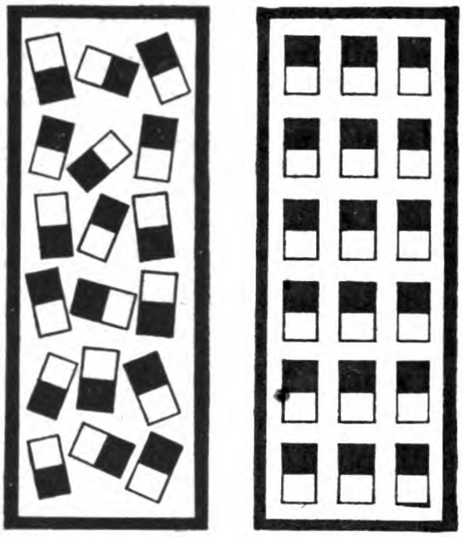


The diagram at the left shows the magnetic field about a bar magnet. At the right is shown the magnetic field between two unlike poles (top) and two like poles (bottom).

Theory of Magnetism. The modern theory of magnetism attempts to account for the magnetization of an object and for some of the observed facts of magnetism.

The basic assumption is that each individual atom of a magnetic substance is, in effect, a tiny magnet with a north pole and a south pole. This magnetism is believed to be due to the motion of the electrons in their orbits. (The flow of electricity always produces magnetism.) In an unmagnetized bar, the arrangement of the atoms is such that all of their magnetic fields are neutralized and exert no magnetic influence at all outside the bar.

In a magnetized bar, it is believed that many, if not most, of the atoms are arranged so that their magnetic fields are aligned in the same direction. Thus the magnetic field is strengthened and extends outside the bar itself.



The bar at the left is unmagnetized; its atoms are disarranged. The bar at the right is magnetized because the atomic poles are aligned.

This theory of magnetism seems highly plausible in view of the many facts of magnetism which it explains.

1. *Magnetic saturation.* There is a limit to which a piece of magnetic material can be magnetized, beyond which its field cannot be made any stronger. Such a magnet is said to be *saturated.* When this condition is reached, it is believed that *all* of the atoms have been aligned with their north poles in the same direction.

2. *Decrease in strength.* Most magnets gradually lose their strength, especially if care is not taken in storing and handling them. Anything which promotes increased atomic motion disturbs the orderly arrangement of the aligned atoms and thereby destroys the magnetism of the object. Heating magnets, dropping or jarring them, storing them with like poles adjacent, and passing electric currents through them weaken the strength of magnets.

3. *Breaking a magnet.* When a bar magnet is broken in two, each half becomes a magnet with a north pole and a south pole.

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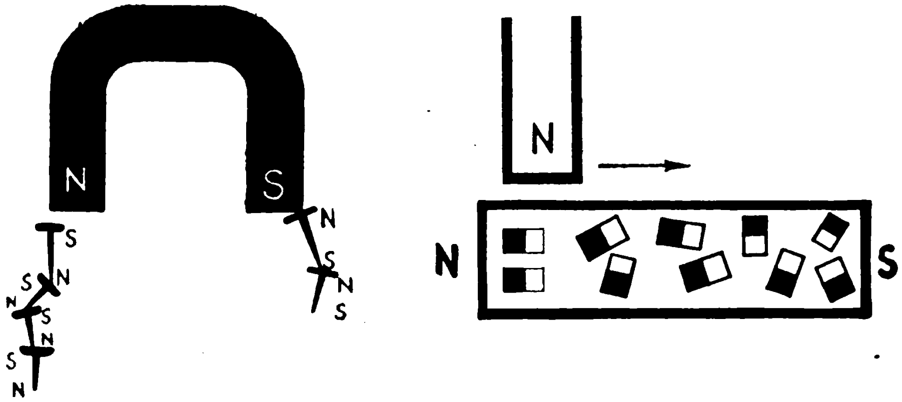
This breaking in two can be continued until the pieces are quite small,—theoretically, until the pieces are the atoms themselves, when they would still be magnets.

4. *Production of magnets.* An unmagnetized iron bar can be made into a magnet simply by holding another magnet close to it. This is called *magnetic induction.* The magnetic lines of force from the magnet pass through the iron bar and align many of its atoms. By magnetic induction a *north* pole is set up in the end of the bar nearest the south pole of the magnet and a *south* pole in the end nearest the north pole of the magnet. Magnetic induction is clear if we remember that the material to be magnetized is composed of atoms which are in themselves minute magnets, but not aligned. When a magnetic field is introduced the atoms are aligned and induced magnetism results. Induced magnetism is usually only temporary and disappears when the magnet is removed. An unmagnetized iron bar can also be made into a magnet by stroking it with a magnet or by using the magnetic field around an electric current. If the material being magnetized is hard steel (cobalt steel, for example), rather than soft iron, the magnetism tends to be permanent.



Induced Magnetism. The U-magnet induces magnetism in each of the iron tacks brought within the magnetic field of the U-magnet. Note that the tacks become magnetized whether or not they actually touch the magnet. In the diagram at the right, the atoms in the magnetized bar are aligned by the N-pole as it passes over them.

Highly permeable materials are very easily magnetized but

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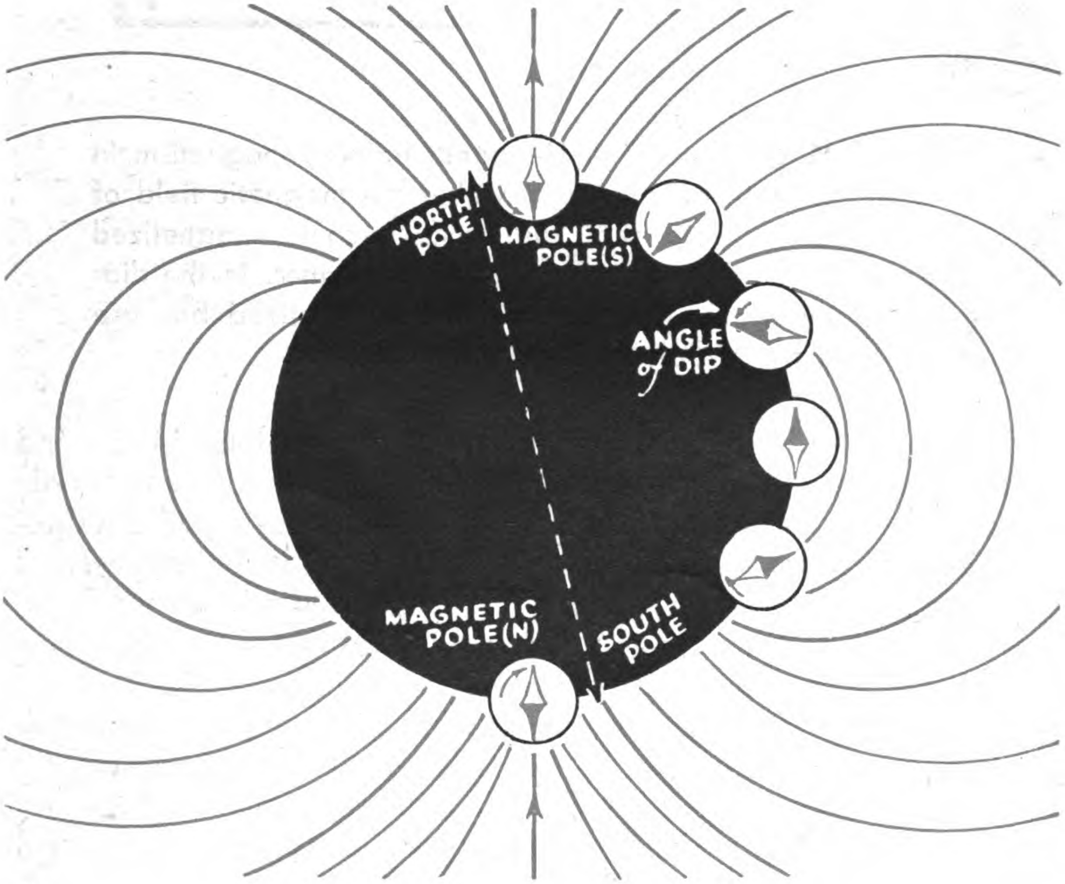
just as easily lose their magnetism when removed from the influence of the magnet. *Retentivity* is the ability of a material to retain its magnetism. In general, materials having high permeability have low retentivity.

Magnetism of the Earth. The earth acts like a huge magnet with one pole located at the extreme north of the middle of Canada just inside the Arctic Circle, and the other pole nearly diametrically opposite, in the Antarctic region. The lines of force that form the earth's magnetic field have been mapped for use by navigators, surveyors, explorers, etc., for finding direction.

In making use of the earth's magnetic field, an instrument called a *compass* is used. It consists of a magnetized needle carefully balanced and supported at its mid-point so that it is free to turn in a horizontal plane. On the inside bottom of the case con-



Magnetic Field of the Earth. Note how the angle of dip is determined by the direction of the earth's magnetic lines of force at that point.

taining the compass, there is usually a circular card marked in degrees from 0° to 360°. This enables the navigator (of a ship or a plane) to determine the angle between the direction in which the craft is going and the direction of the compass needle. (The card may be attached to the needle and rotate with it. A fixed pointer at the edge of the card gives the reading in this case.)

To increase the accuracy of the compass reading, magnetic compasses on ships and aircraft are *compensated* to allow for iron and steel in the ship.

Magnetic Declination. The earth's magnetic poles and its geographic poles do not coincide. The angle by which a compass needle deviates from geographic north at any location is called the *declination* of that locality. Thus in New York City, the average declination is about 10° west, which means that a compass needle points in a direction 10° west of true north. The declination at Cincinnati, Ohio, is 0°. Places to the west of Cincinnati have east declination.

Magnetic Inclination. A perfectly balanced magnetic needle placed parallel to the magnetic field and free to pivot in a vertical plane about a horizontal axis, will dip from the horizontal at most locations on the earth and arrange itself so that it is parallel with the earth's magnetic lines of force. The angle such a *dipping needle* makes with the horizontal is called the *inclination* of the locality. In New York City, the dip is about 70°. At the magnetic poles the dip would be 90°.

Induction by the Earth's Magnetic Field. If a bar of soft iron is set parallel to the earth's lines of force for a given locality, and is dipped parallel to a dipping needle and hammered on one end, the bar will become a temporary magnet. The hammer blows disturb the arrangement of the atoms, and the magnetic force of the earth aligns many of these atoms with their north poles in the same direction; that is, magnetism is induced in the bar by the magnetism of earth. Bars of iron driven into the earth vertically or left standing in a vertical position, as iron fence posts, are similarly magnetized. In the northern hemisphere, the top of the bar will be found to be a south pole.

Changes in the Earth's Magnetism. The earth's magnetic field undergoes continual, though gradual, change. That is, the magnetic poles shift their locations very slowly. Magnetic declination of any place on the earth is not exactly the same every year.

Magnetic storms, seemingly associated with sunspot activity, occur irregularly over the earth. These magnetic disturbances produce sudden and violent fluctuations in the compass reading. They may completely disrupt long-distance telephony, telegraphy, and radio communication, and they produce greatly increased static on radios.

Types of Compasses. All compasses are direction-finders. The common type mentioned on page 6 is a simple magnetic compass. When this compass is subjected only to the magnetic field of the earth, it indicates accurately the direction of magnetic north. When allowances are made for magnetic declination, the direction of geographic north is found. If, however, the magnetic compass is used in the vicinity of magnetic materials, the magnetic field of these materials will make the compass reading inaccurate. These undesirable magnetic fields are eliminated by "compensating" the compass. Small magnets are set near the compass in such a way as to neutralize all magnetic fields except that of the earth.

Because of the special problems of air navigation, modifications of the magnetic compass and the development of new direction-finders became necessary. Early airplanes carried the ordinary type of magnetic compass, but the compass had to be located on the floor of the plane so that the pilot could see the dial. Modern compasses are mounted in the instrument panel and have a glass in the side of the compass case. The card on which the compass directions are marked is mounted on the needle and turns with it. During flight, the compass needle and hence the card remain practically motionless. In addition, the airplane compass is filled with a liquid to overcome oscillation and thus steady the needle, which would otherwise swing too much when the plane vibrated to be useful. When the reading of the compass changes, it means that the plane has turned about the compass needle and card. This reading is obtained by reference to a line called the *lubber line,* which is marked down the center of the glass cover of the compass so that it is in line with the longitudinal axis of the plane. The reading on the dial just back of the lubber line indicates the direction in which the plane is pointed. A new variety of magnetic compass has a reference index pointer which can be set by hand to the correct course. The pilot's task is then simply one of directing the plane so that the reference pointer and the lubber line coincide.

When a plane is turning, the extra swing and oscillation caused by the turning process makes the magnetic compass unreliable in helping the pilot turn the plane the correct number of degrees. The *directional gyro* is used to supplement the magnetic compass during the turn. The directional gyro is an air-driven gyroscope which operates a dial similar in appearance to the one on the magnetic compass. The gyro's dial is set to correspond with the reading of the compass just before the turn is begun. The instrument will give fairly accurate readings for several minutes—long enough to negotiate the turn.

MULTIPLE ANSWER TEST

Check all correct answers; there may be more than one.

I. *Two magnetic poles*

1. _____ attract each other if they are both north poles;
2. _____ repel each other if they are both south poles;
3. _____ attract each other if one is north, and the other south;
4. _____ attract or repel each other with one-fourth as much force if the distance between them is doubled.

II. *Magnetic lines of force*

5. _____ frequently cross one another;
6. _____ repel one another;
7. _____ tend to contract like stretched elastic bands;
8. _____ run from the north pole to the south pole of a magnet.

III. *An unmagnetized steel bar may be magnetized by*

9. _____ holding another magnet near to it;
10. _____ wrapping insulated wire around it, and passing an electric current through the wire;
11. _____ bending it U-shaped.

QUESTIONS

1. What is the difference in behavior between soft iron and hard steel after they have been left for some time in a magnetic field and later removed from the field?

2. Can a magnet be made with only one pole? Explain.

3. State three ways in which a magnet may be de-magnetized.

4. How can you determine whether a piece of steel is magnetized or not?

5. Iron posts placed in the ground are found, after some time, to be magnetized. Which end would be found to be a north pole? Explain.

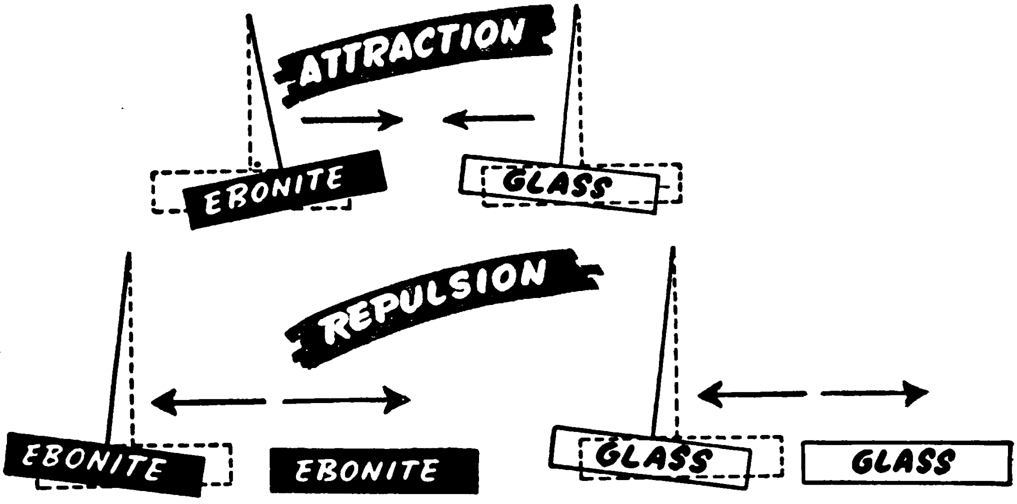
6. How might a magnetic compass be used to detect the presence of large bodies of iron ore?

7. Explain how a magnet attracts several nails, each hanging from the other.

TWO—

STATIC ELECTRICITY

Electric Charges. An ebonite (hard rubber) rod is rubbed with fur and the rod suspended from a silk thread. If a second ebonite rod is similarly rubbed and brought near the suspended rod, it will be found that the suspended rod is repelled. If the same procedure is repeated using glass rods rubbed with silk, it will be found that the two glass rods will repel each other. But if the rubbed glass rod is brought near the rubbed ebonite rod, the two will be found to *attract* each other. Apparently, rubbing the ebonite rod with fur and the glass rod with silk imparted a special property to the rods. Objects which behave in this manner are said to be *charged* or *electrified.* Many such experiments have resulted in two important conclusions.



Unlike charges attract; like charges repel.

1. *There are two kinds of electric charges*—the kind produced on ebonite by rubbing it with fur, and the kind produced on glass by rubbing it with silk. The terms suggested by Benjamin Franklin to distinguish between these two kinds of charges are still used, namely, *positive* for the charge or electrification on the ebonite, and *negative* for the charge on the glass. It has further been determined that both kinds of charges occur in definite

units, and that one unit of positive charge exactly equals one unit of negative charge.

2. *Like charges repel each other and unlike charges attract each other.* The force of attraction or repulsion depends upon the magnitudes of the charges and varies inversely as the square of the distance between them.

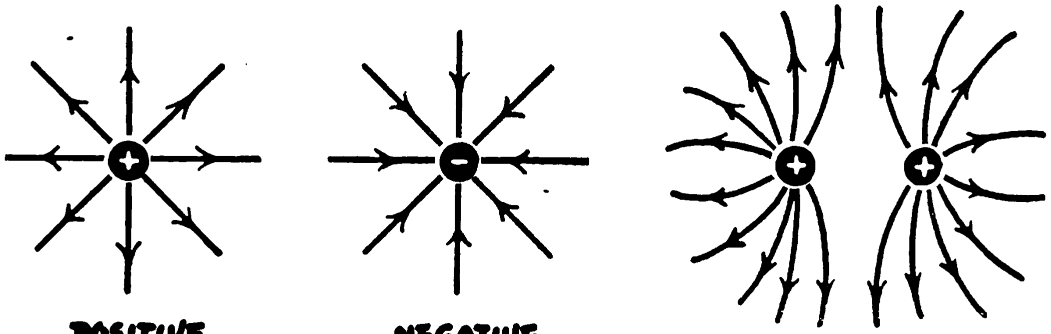
Differences Between a Magnetized Body and an Electrified Body. 1. A charged body attracts any material. A magnetized body attracts only magnetic materials, such as iron, steel, nickel, and cobalt.

2. All materials may be charged, but only magnetic materials can be magnetized.

3. A body may be charged either negatively or positively. A magnet must have two poles.

4. A charged body loses some or all of its charge if touched with any uncharged body. A magnet does not lose any of its magnetism by touching other bodies.

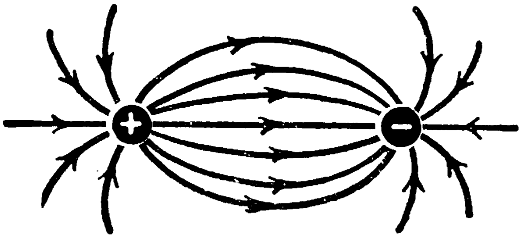
Electric Field of Force. An electric field of force surrounds all charged bodies. As in the case of magnetism, this field can be represented by imaginary lines of force indicating the direction and intensity of the field. The diagrams show the conventional



POSITIVE

NEGATIVE

TWO LIKE CHARGES (REPULSION)



TWO UNLIKE CHARGES (ATTRACTION)

Electric Field About Unit Charges

representations of the fields of force surrounding bodies possessing unit positive and negative charges.

Work is required to overcome the force of repulsion and bring two similar charges closer together. Work is also required to overcome the force of attraction if two unlike charges are to be separated.

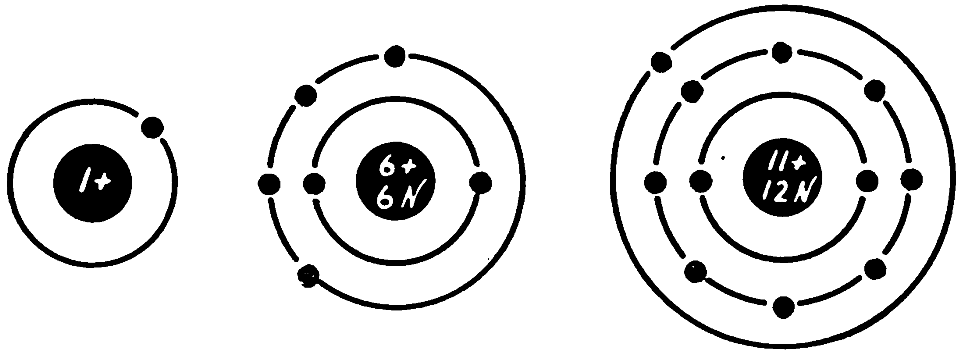
Electrical Nature of Matter. The production of electric charges and the interpretation of their effects can best be explained by the theory that *all ordinary matter is composed of positive and negative electricity in equal amounts.* In other words, there is reason to believe that both positive and negative electricity are everywhere and in all things, such as glass, ebonite, paper, metals, water, air, etc. This belief is commonly explained by the *electron theory* of matter.

Positive electricity occurs in units called *protons,* while the units of negative electricity are called *electrons.* The electron and the proton each have the same charge, although the weight of the proton is about 1850 times the weight of the electron. The proton has a relative weight (compared with a hydrogen atom) of practically 1; thus the electron weighs approximately $1/1850$ as much as the hydrogen atom. There is some evidence to suggest that the proton is composed of a *positron* and a *neutron,* the positron being a positively charged particle having the same weight as the electron, and the neutron having a relative weight of 1 but no charge.

The Structure of Atoms. For many years it was believed that the atom was the smallest subdivision of matter. The development of the electron theory changed this belief, and suggested that *all atoms are normally neutral bodies composed of equal numbers of protons and electrons.* Furthermore, the atoms of the different elements differ only in the number of protons and electrons, and in their arrangement within the atoms; in other words, the electrons and protons from one element are identical with those from any other element.

According to present beliefs, atoms are constructed according to the plan of our solar system. They have a heavy, positive nucleus (corresponding to the sun) containing all the protons, and, therefore, practically all the mass of the atom. The electrons are thought to revolve around the nucleus in paths called *orbits,* much in the same manner that Earth, Mars, Venus, and the other planets revolve around the sun. These electrons are held within their orbits by the force of attraction existing between the nuclear protons and the planetary electrons.

The hydrogen atom has the simplest structure. It has one proton for a nucleus and one electron revolving around it. Other atoms are more complex, having many protons in their nuclei and an equal number of electrons revolving in the outside orbits. (The nucleus is believed also to contain neutrons (*n*), neutral particles weighing about as much as a proton.) The diagrams show the probable structure of the atoms of several elements.



Hydrogen **Carbon** **Sodium**

Note that in each case the number of protons (+) equals the number of electrons (—). The electrons are shown in red.

How Bodies Become Charged. The electrons within the atoms of all substances are in constant motion. There is a tendency, moreover, for some of these moving electrons to leave the atoms to which they belong and move to neighboring atoms. These moving or circulating electrons are called "free" electrons.

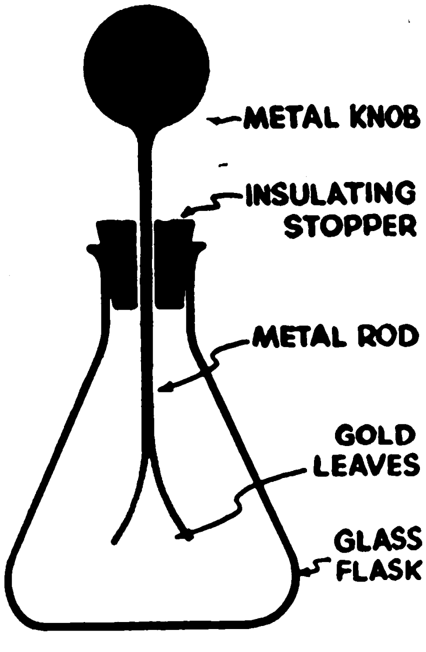
Some substances have more free electrons than others. Consequently, when two dissimilar substances are placed in contact, the substance with more free electrons will lose some of these electrons to the other substance with which it is in contact. The substance which loses electrons becomes positively charged; the substance which gains electrons becomes negatively charged.

Bodies become charged only by acquiring or losing electrons and not by any transfer of protons, which are in the nuclei of atoms and are not free to move.

When the ebonite rod was charged by contact with fur (the rubbing merely brought more atoms into contact; friction has nothing to do with it), some of the electrons left the fur and attached themselves to the rod. Likewise, when the glass rod was rubbed with silk, electrons moved from the glass to the silk. Whenever electrification is caused by contact, two opposite kinds of charges are produced in equal amounts.

Insulators and Conductors. Different substances vary greatly as to the freedom of motion of their electrons. Substances in which the free electrons move readily are called *conductors.* Metals are good conductors because their free electrons move easily from one point to another within the metal. Silver, copper, and aluminum are examples of excellent conductors. Non-metals are generally poor conductors. A very poor conductor is known as an *insulator,* some examples of which are: mica, air, paper, rubber, and certain plastics.

Charges can be built up or localized on an insulator or insulated conductor; that is, the electrons will not readily flow away from the insulator or toward it. For this reason, insulators or insulated conductors are used when observing the phenomena of static electricity.



CHARGES MOVE ON PARTS SHOWN IN RED

The Gold Leaf Electroscope

The Electroscope. The electroscope is a device for detecting the presence of an electric charge, and also for determining whether this charge is positive or negative. The gold leaf electroscope consists of a glass flask with an insulating stopper, through which a metal rod passes. A metal knob is fastened to the outer end of the rod and two very thin leaves of gold are fastened to the end of the rod inside the flask. Other kinds of metal foil may be substituted for the gold. The flask, or other housing, of the electroscope prevents the delicate leaves from being affected by drafts of air, while the insulating stopper

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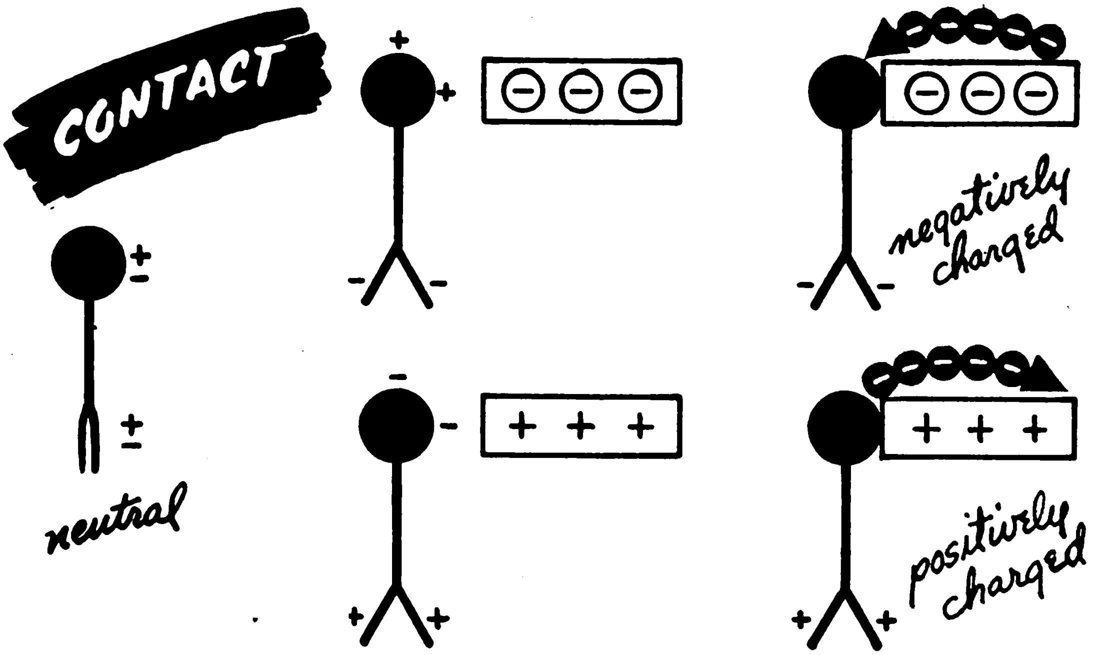
(sulfur, rubber, etc.) prevents the leaves of the electroscope from losing their charge.

Charging the Electroscope by Contact. If a charged body is touched against the knob of an electroscope, it will be found that the gold leaves of the electroscope will diverge, indicating that like charges have been produced upon the leaves, causing them to repel each other. The extent to which the leaves diverge is an indication of the amount of charge. The reason for this phenomenon becomes apparent upon examination of the diagram. Normally, the positive and negative charges within the electroscope balance each other, leaving it neutral. When a charged body (assume it is negative) is brought near the knob of the electroscope, some of the electrons in the knob are repelled to the gold leaves, thus causing them to diverge. The knob now is deficient in electrons. As the charged body touches the knob, the electrons flow from the charged body into the knob. When the charged body is removed, the electroscope is left with an excess of electrons; the gold leaves remain diverged, and the electroscope is said to be

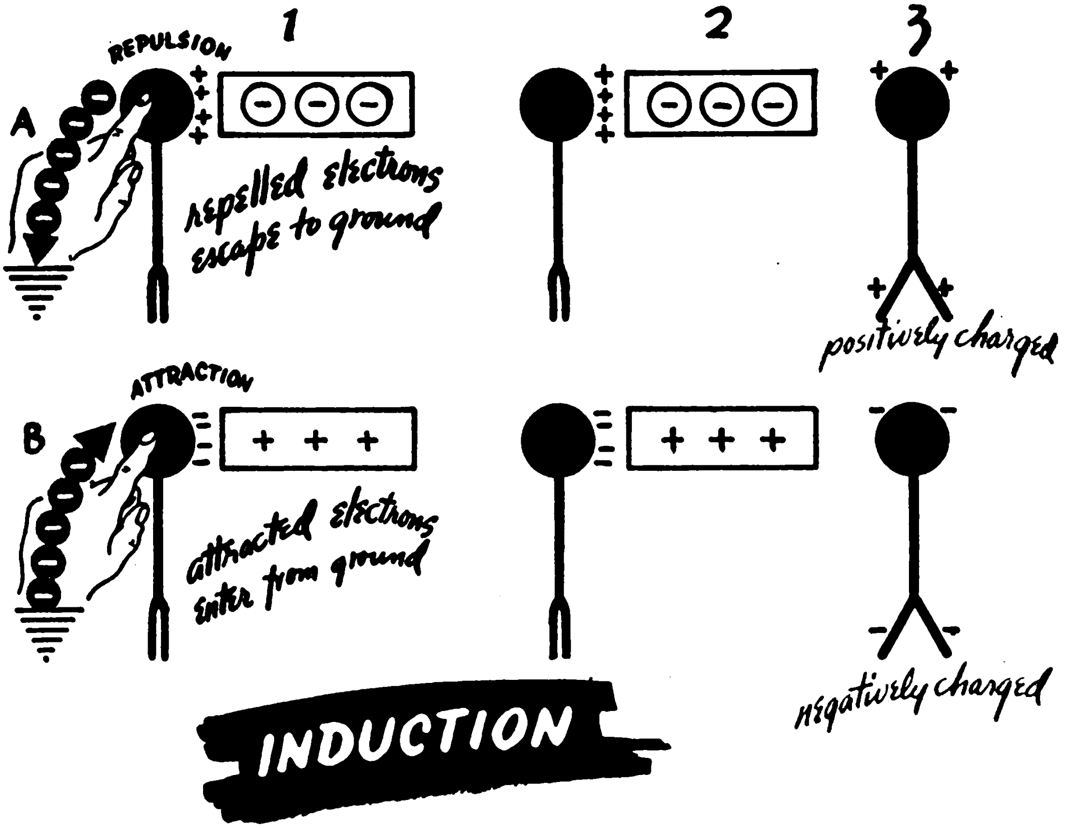


Charging by Contact. Since all matter is composed of protons and electrons, only a deficiency or excess of electrons imparts a charge to a body.

negatively charged. If a positively charged body is touched to the knob, the electrons will leave the electroscope, leaving it positively charged.

Whenever any body is charged by *contact,* the sign of the charge produced is the *same* as the sign of the charge producing it.

Charging the Electroscope by Induction. As we have just seen, even the approach of a charged body is sufficient to move the electrons in an electroscope, and cause the leaves to diverge. We have also seen that the force of attraction and repulsion is such as to drive like charges as far apart as possible and to bring unlike charges as closely together as possible.


1
2
3
REPULSION
A
repelled electrons escape to ground
positively charged
ATTRACTION
B
attracted electrons enter from ground
negatively charged
INDUCTION

Charging by Induction. The charged and charging bodies do not touch; electrons enter or leave the body being charged through the action of an electric field of force.

1. *Inducing a Positive Charge.* If a negatively charged body is brought *near* (but not in contact with) a neutral electroscope (diagram A), some of the electrons in the knob will be driven

away from the charged body. If we now provide a path of escape for the negative charges by touching the knob of the electroscope with the finger (1) or with any other conductor connected with the earth (ground), the negative charges will leave the electroscope. If the finger is first removed (2), thus breaking the link with the ground, and then the charged body is removed, the electroscope will be found to be charged positively (3).

2. *Inducing a Negative Charge.* To induce a negative charge (diagram B), a positively charged body is brought near the electroscope. When the knob is touched with the finger (1), electrons are attracted from the earth into the electroscope. When first the finger (2) and then the charged body are removed, the electroscope will have an excess of negative charges and thus will be negatively charged (3).

Whenever any body is charged by *induction,* the sign of the charge produced is *opposite* to the sign of the charge producing it.

Determination of the Sign of the Charge. To determine whether the charge on a body is positive or negative, a *charged* electroscope is used. Suppose a charged body is brought near a negatively charged electroscope and the leaves are observed to diverge still more. We know that like charges repel. Since the leaves were already negative, additional electrons must have been repelled from the knob into the leaves to make them diverge still more. Hence the unknown charge on the body must have been negative.

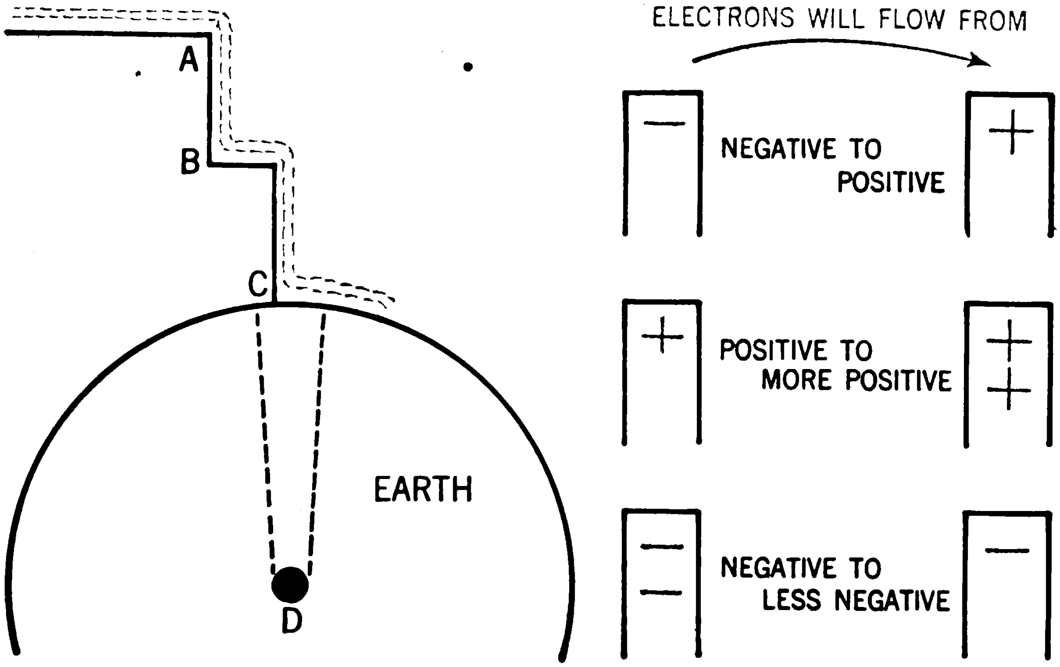
The following table shows the effect of bringing (1) a positive body, (2) a negative body, near (a) a neutral electroscope, (b) a positively charged electroscope, and (c) a negatively charged electroscope.

	(a) Neutral Electroscope	(b) Positively Charged Electroscope	(c) Negatively Charged Electroscope
1. Positive body	Leaves diverge	Leaves diverge farther	Leaves come together
2. Negative body	Leaves diverge	Leaves come together	Leaves diverge farther

Thus the presence of a charged body can be detected by the use of either a neutral or a charged electroscope, but the sign of the charge can be determined only by the use of a charged electroscope of known sign.

Electric Potential. Potential energy is the energy possessed by an object by virtue of its position. Thus, the water at the top of Niagara Falls possesses potential energy because of its position in the gravitational field of the earth. As the water pours over the brink of the falls, this potential energy is converted into kinetic energy.

In a similar manner a charge in an electrical field possesses potential energy. This energy is measured by the amount of work required to move the charge from infinity up to that point and is similar to the work required to raise water from the center of the earth to the top of Niagara Falls. (1) If the work must be done to move a positive charge up to the point, the point is said to be at positive potential. (2) If the work must be done to move a negative charge up to the point, the point is said to be at negative potential.



Electrons flow from low to high potential.

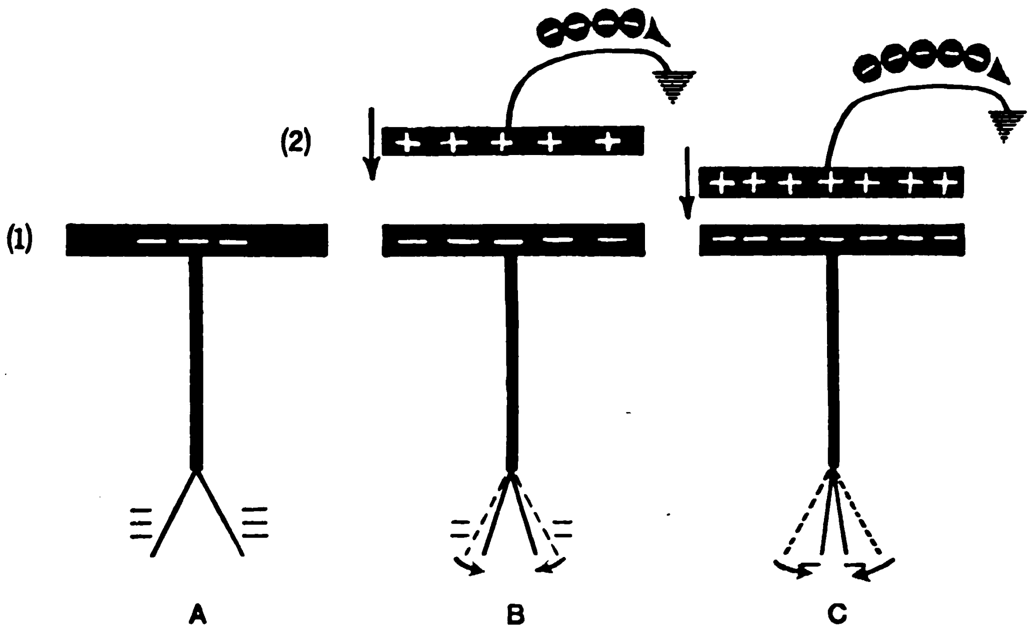
Potential Difference. We said above that when the water at the top of Niagara Falls fell to the bottom of the falls the potential energy stored at the top was used up. Actually, this is not strictly true. If there were a shaft at the bottom of the Falls extending to the center of the earth, we know that the water would fall to the center of the earth. Therefore, the water at the bottom of the Falls still possesses some potential energy. The work done by the falling water was really a measure of the *difference* in potential energy between the top and the bottom of the Falls. An examination of the diagram will make this clearer. The water at point *A* will flow to point *B*. The water at point *B* will also flow to point *C*. The water at point *C* would (if there were a shaft) flow to point *D*. A power station at point *B*, in harnessing the work performed by the water falling from *A* is really utilizing only the *difference in potential* energy between points *A* and *B*. The water at *B* still has potential energy, which can be utilized by a power station at the lower level, *C*.

A parallel situation exists with regard to electric potential. The free electrons in a conductor will flow from a point of low (or relatively negative) potential to a point of high (or relatively positive) potential. The difference in potential energy between two given points is what causes electrons to flow from one point to the other until the potential of the two points is the same. An electric difference in potential exists between two points if (1) one is positive and the other negative, or (2) both are positive but one is more positive than the other, or (3) both are negative but one is more negative than the other. The diagram illustrates the flow of electrons in these three situations.

The flow of electrons produced by a difference in potential constitutes an electric current. We get only intermittent currents from a static electricity machine because the potential difference that is built up by the separation and localization of positive and negative charges drops to zero every time a spark discharge permits the electrons to reunite with the positive charges. Chemical cells, batteries, and mechanical generators maintain a steady difference of potential and so produce continuous currents of electric charges. Difference of potential (p.d.) is measured in *volts. Electromotive force* (emf or "electron-moving force") and *electrical pressure* are other terms used to express a difference in potential.

The Condenser. Any charged conductor can be looked upon as a storehouse or source of electric charge. If an uncharged conductor is connected to it, some of the charge in this "storehouse" will flow into the second conductor. In certain applications of electricity it is desirable to store large quantities of charge upon a conductor or group of conductors, so that these conductors can act as sources of electric charge. A device which is designed so that it will readily hold large amounts of charge is called a *condenser.*

In general, practical condensers consist of two conductors quite close to each other, but separated by an insulator or *dielectric.* The conductors are usually thin sheets or plates of metal. The action of this condenser depends upon electrostatic attraction between charges of opposite sign upon the two conductors, as will now be explained.



The Principle of the Condenser

In the diagram, *A* is a negatively charged electroscope, with a metal plate (1) instead of a knob at the top. Plate (1) has a certain amount of negative charge upon it. There is also a negative charge on the leaves of the electroscope, causing them to diverge. We shall now see how the charges can be redistributed so that more negative charge appears on plate (1).

In *B,* a grounded metal plate (2) has been brought close to plate (1). As a result, the leaves of the electroscope have moved closer together, indicating that some of their negative charge has left them and moved onto plate (1). The explanation is as follows. Electrons on plate (2) have been repelled to the ground by

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the electrons on plate (1). The resulting positive charge on plate (2) has attracted additional electrons from the leaves into plate (1). In other words the ability of plate (1) to hold a negative charge has been increased by the approach of the grounded plate (2).

If plate (2) is brought closer to plate (1), as shown at *C*, the electroscope leaves will come still closer together, showing that more negative charge has been drawn onto plate (1) and bound there by the increased positive charge on plate (2). We thus see that *the ease with which each plate holds a charge is increased when the distance between them is decreased.*

The charge on each plate will also increase if a pane of glass or other non-conductor is inserted between the plates. The glass increases the strength of the electric field between the plates, thus strengthening the attractive forces upon which the condenser action depends. This phenomenon is similar to that produced by inserting a soft iron core in a magnetic field to increase the field strength. Any non-conductor or dielectric will have a similar effect on the condenser—the amount depending on a property called the *dielectric constant* of the substance. Dielectric constant in electricity is similar to permeability in magnetism.

As might be expected, *increasing the area of the plates will also increase the amount of charge on the plates.*

The Capacitance of a Condenser. The relative ease with which a condenser holds or stores a charge is called its *capacitance.* We have just seen that the capacitance of any condenser depends upon the distance between its plates, the kind of dielectric between them, and the area of the plates.

The capacitance of a condenser is like the volume of a gas container. By increasing the pressure, more and more gas molecules can be forced into the container even though the volume does not change. Similarly, by increasing the electrical pressure more and more charge can be forced onto the plates of the condenser.

Experiments have shown that the amount of charge on a given condenser is directly proportional to the potential difference or electrical pressure acting upon the plates. On the other hand, applying the same potential difference to different condensers will result in different accumulations of charge in proportion to the capacitance of each particular condenser. That is,

$$\text{Charge} = \text{Capacitance} \times \text{Potential Difference}$$
$$Q = CE$$

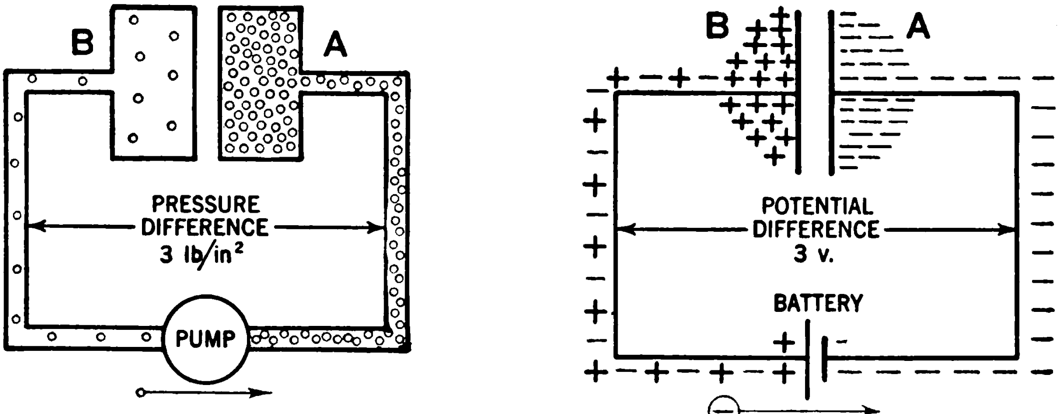
If Q is measured in *coulombs* (p. 262), and E is measured in *volts,* then C is measured in *farads.*

Back EMF of a Condenser. The right-hand diagram on the opposite page shows a condenser connected to a source of voltage. The electrons from the negative terminal flow to plate (A), where they produce a negative potential. The negative plate (A) repels electrons from plate (B), thus producing a positive potential on plate (B). The electromotive force of the battery or generator continues to drive electrons to plate (A) and draw electrons from plate (B) until the difference in potential across the two plates is the same as that across the two terminals of the battery or generator.

A "back pressure" builds up at the plates of the condenser as the charge on it accumulates. The electrons already on plate (A) tend to repel additional electrons coming from the negative terminal of the battery. Equilibrium results when this "back pressure" of the electrons on plate (A) exactly equals the forward pressure from the battery.

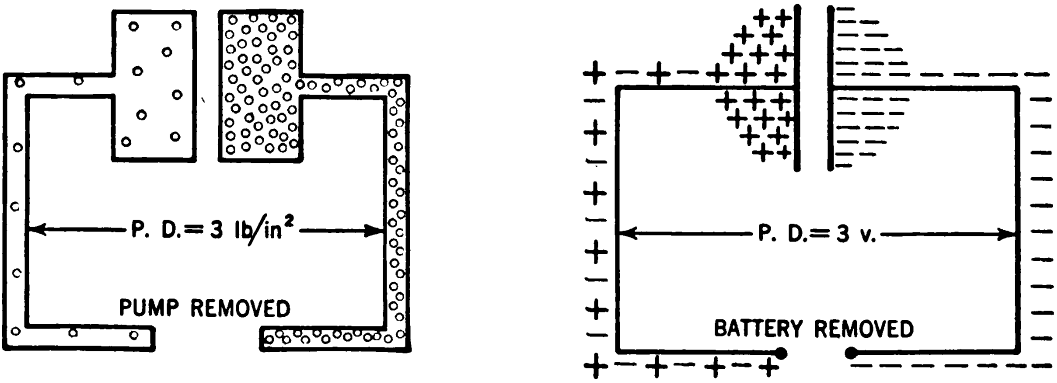
This back pressure may itself be used as a source of voltage. If after charging the condenser, the battery is removed, the charged condenser is left with a potential difference between its plates. If a conductor is then connected from one plate to the other, electrons will flow from the negative plate to the positive plate through the conductor.

The concept of back emf will be better understood if an analogy is drawn between electric pressure and air pressure. In the left diagram, the molecules of air would be equivalent to electrons. Assume that two pipes are connected to a pump as shown in the diagram and that the pump is capable of creating a pressure difference of 3 lb/in^2. The pump draws molecules of air from pipe (B) and pushes them into pipe (A). This continues until a difference in pressure of 3 lb/in^2 is produced between the two pipes, at which time the air pressure in pipe (A) will counterbalance the force exerted by the pump and no additional air molecules can be pumped into it. If the pump is now disconnected from the two pipes and the latter are connected as shown, it is apparent that the air will flow from one pipe to the other in the direction of the greater force. This is exactly what happens with the electrons in a condenser.

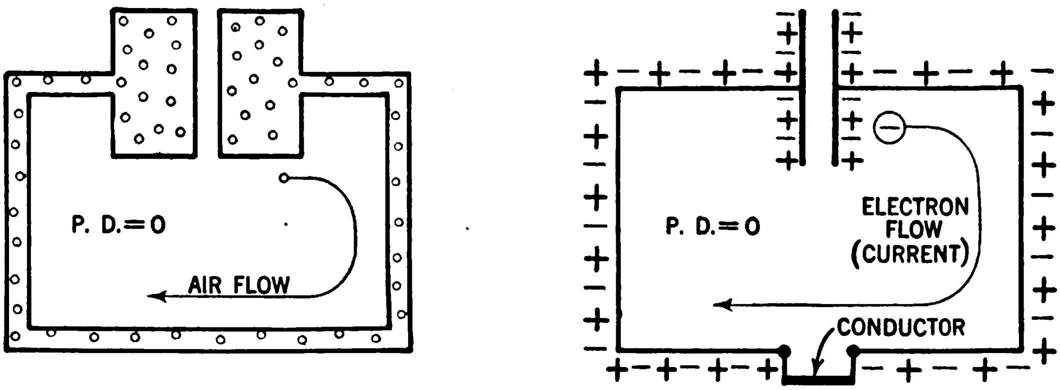


AIR MOLECULES PUMPED FROM B TO A

ELECTRONS PUMPED FROM B TO A



CONDENSER CHARGED



PIPES CONNECTED

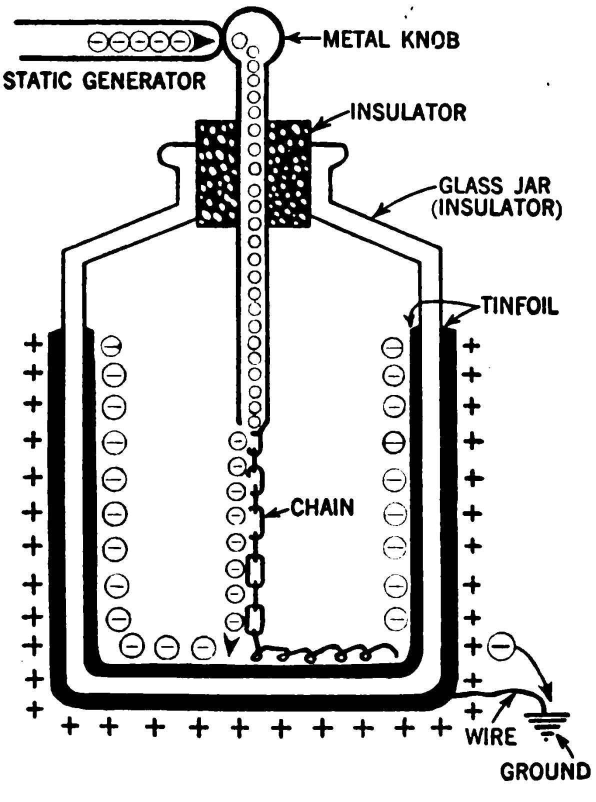
CONDENSER DISCHARGED

Action in a Condenser during Charging and Discharging

Breakdown Voltage. The electrical field between the plates of a condenser (or any two charged bodies) tends to break the atoms of the dielectric apart, and liberate some of its electrons. As the voltage between the plates is increased, this disruptive stress increases until, finally, the dielectric does break down. As soon as this happens, the material ceases to be an insulator, and the electrons from the negative plate flow through the dielectric to the positive plate. This *discharge* occurs in the form of an extremely hot spark (or *arc*). The voltage at which the dielectric breaks down and the condenser discharges is called the *breakdown voltage.* This is the practical limit on the voltage that can be applied to a condenser.

The breakdown voltage decreases as the two charged plates (or conductors connected to them) are brought closer together.

The Leyden Jar. The Leyden jar is a condenser. It consists of a glass jar coated inside and out with tinfoil. A metal rod passing through an insulating stopper makes contact with the inside coating through a metal chain.

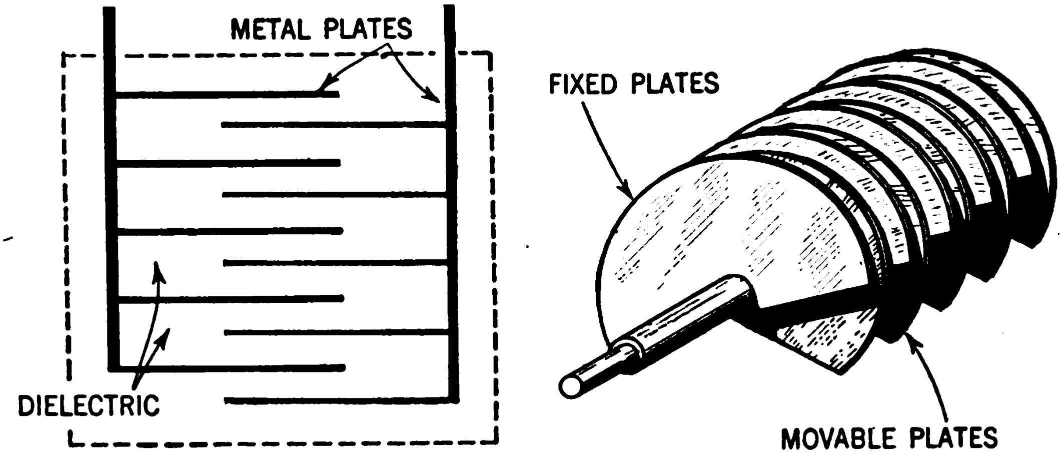


The Leyden jar is a condenser.

The Leyden jar is usually charged by charging the inside coating while the outside coating is grounded. The charge placed on the inside coating produces an opposite charge in equal amount on the outside coating by induction. Thus, a potential difference is produced between the two coatings. These unlike charges attract each other through the dielectric (in this case, glass) and neither one escapes.

A charged Leyden jar may be discharged by connecting the two coatings to each other by a wire or by a curved metal rod provided with an insulated handle. If one end of this rod is touched to one coating and the other end is brought near the other coating of a charged Leyden jar, a large spark will be obtained. A ¼-inch spark indicates a potential difference between the coatings of about 10,000 volts.

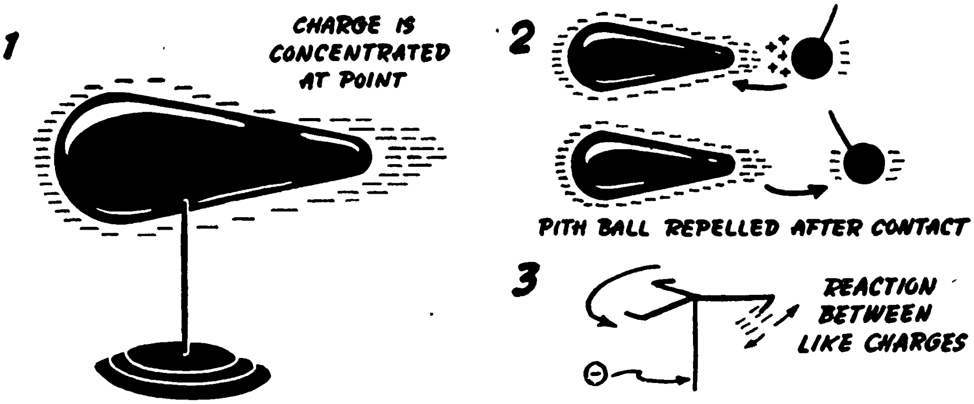
The Leyden jar was one of the early condensers. Modern commercial condensers vary in materials and in construction. They may be made of silver and mica, tin foil strips and waxed paper, aluminum foil and aluminum oxide film, etc. They may have a fixed capacitance, or may be *variable*. Condensers have many applications in connection with induction coils, alternating current circuits, and radio, all of which are discussed later.



Fixed and Variable Condensers. The capacitance of the variable condenser is changed by rotating the movable plates, which thus changes the effective area of the plates.

Discharge from Point and Sphere. As we have just seen from our discussion of the Leyden jar, the electric charges on an insulated body collect on the surface of the body. If the body is in the form of a sphere, the charges will be distributed equally over the surface of the sphere. If the sphere is elongated, however, we find that the charges tend to concentrate at the most pointed end. The more pointed the body is, the greater is the relative concentration of electric charge at the point. This property is illustrated in the diagram (1), on page 26.

If a pith ball covered with tin foil and suspended from a silk thread is brought near the pointed end of a negatively charged body, the electrons on the ball will be repelled to the far side of the ball, leaving the side nearest the point positively charged. The ball will be attracted to the point until it touches, at which time electrons will leave the point and enter the ball, charging it negatively. The charged ball will now be repelled from the similarly charged point. This action will also take place between a charged point and particles of matter in the air. As a particle touches the point it becomes charged as the pith ball was charged and is similarly repelled from the point. If sufficient number of particles are thus repelled, an effect known as an "electric wind" is produced. As shown by the diagram (3), the force of repulsion between the charged point and the particles is sometimes great enough to cause the point to move.


1
CHARGE IS CONCENTRATED AT POINT
2
PITH BALL REPELLED AFTER CONTACT
3
REACTION BETWEEN LIKE CHARGES

In diagram 1, the minus signs indicate the distribution of charge on the surface of the body. The charge is always more concentrated where the curvature of the surface is greater, as at a point. Diagram 2 shows that a pith ball is first attracted to a charged body, then repelled after contact. The effect is most marked at the pointed end of a charged body. Diagram 3 shows that the repulsion of air molecules from the ends of a pointed pinwheel will cause the pinwheel to rotate by reaction.

Ionization of the Air. Air is ordinarily an insulator, and all the molecules and atoms in it are neutral. If, however, some electrons are separated from their atoms, the latter become charged particles, or *ions,* which move when a charged body is brought near them. If the charge on a pointed body is large enough, it will repel electrons from nearby molecules of air. The positively charged ions which are left will attract electrons from the point and thus cause it to discharge. In other words, the ionized air becomes a conductor. This tendency on the part of charged bodies provided with a point to discharge is made use of in lightning rods.

When lightning strikes the earth, it usually hits tall or pointed objects on the ground. A lightning rod projecting above a house will attract the stroke and carry it safely to the ground.

Lightning. Lightning is an electric discharge which takes place as a result of the difference in potential between charged clouds and the earth and the ionization of the air which acts as an insulator between them. When warm, moist air rises, water vapor is formed by condensation when the cold of high altitudes is reached. As larger droplets of water are formed they become positively charged. The finer spray is negatively charged. In this manner, a difference in potential is set up between the larger droplets and the fine spray. Under the influence of this voltage (usually tremendous), the air breaks down and becomes conducting. A discharge of electricity or lightning may follow. This discharge may occur between clouds or between a highly charged cloud and the earth, or objects (trees, houses, etc.) on the ground. The enormous energy released during the electrical discharge is sufficient to produce searing heat and blinding light.

Lightning rods are installed on buildings to prevent the destructive effects of uncontrolled lightning. If, for example, a positively charged cloud is formed, an equal and opposite charge is induced in the earth nearby. If a well-grounded pointed rod is provided, electrons will flow from the earth to the tip of the rod. The air surrounding the rod tip will be slowly ionized and the electrons on the rod will gradually leak off, thus reducing the difference in potential between the cloud and the earth. Sometimes this difference in potential is too great to be dissipated slowly in this manner and a lightning discharge takes place nevertheless. The bolt will strike the rod and, since the rod is a good conductor and is well grounded, the electric discharge will pass harmlessly into the earth.

During a lightning storm you should avoid isolated trees or buildings, open windows, or large bodies of metal. If you cannot keep dry and stay indoors, the safest places to be are in an all-metal automobile, dense woods, a cave, or foot of a high cliff.

BEST ANSWER TEST

1. The effects of static electricity are associated with the (1) motion; (2) field; (3) direction; (4) magnetism—of electric charges.

2. Two similarly electrified bodies will (1) attract each other; (2) neutralize each other; (3) repel each other; (4) condense.

3. To give an uncharged body a positive charge, (1) add protons; (2) add electrons; (3) remove protons; (4) remove electrons; (5) touch it with a proof plane.

4. If the force of attraction between two charged bodies is 9F, and the distance between them is reduced to ⅓ as much, the force will become (1) 27F; (2) 3F; (3) 12F; (4) 81F.

5. Modern beliefs hold that atoms (1) are indivisible; (2) have a neutral core with electrons around it; (3) have a positive core with protons around it; (4) have a positive core with electrons around it; (5) have a negative core with protons around it.

6. The electroscope is a device for (1) analyzing electric charges; (2) producing electric charges; (3) neutralizing electric charges; (4) isolating electric charges.

7. An electroscope has a positive charge, and when a charged body is brought nearby, the leaves diverge still more. The sign of the charged body is (1) neutral; (2) negative; (3) positive; (4) unknown.

8. An electroscope has a negative charge. A negatively-charged body is brought near it, the electroscope is grounded momentarily, and the charged body is then withdrawn. The electroscope will be (1) charged positively; (2) charged negatively; (3) neutral; (4) broken.

9. An electrical condenser (1) creates electric charges; (2) stores electric charges; (3) destroys electric charges; (4) consists of two insulating plates separated by a conductor.

10. Lightning occurring during an electrical storm (1) is really quite harmless; (2) is really a condenser discharge; (3) never strikes twice in the same place; (4) has no relation to static electricity.

ASSOCIATION TEST

I

11. ______ Silver, copper, iron
12. ______ Sulfur, glass, rubber
13. ______ Measure of potential difference
14. ______ Increased capacity of condenser
15. ______ Used to detect electric charge
16. ______ Electromotive force
17. ______ A simple condenser
18. ______ Practical unit is microfarad
19. ______ 6.28 × 10^{18} electrons
20. ______ 2 factors determining Q of a charged condenser

II

1. Leyden jar
2. Voltage
3. Insulators
4. Coulomb
5. Plates brought closer together
6. Plates moved farther apart
7. Conductors
8. Electroscope
9. Proof plane
10. Capacitance

QUESTIONS

1. Mention two ways in which free electrons may be obtained.

2. Describe a simple experiment to show the difference between an electrified body and a non-electrified body.

3. Explain in physical terms each of the following statements of fact: (*a*) A positively charged body will be discharged if a glowing body is brought near it. (*b*) Lightning is a condenser discharge. (*c*) A condenser may be used to store electricity. (*d*) An electroscope is used to determine the kind of electric charge.

4. State one method of charging an electroscope so that it is in proper condition to test the charge of another electrified body.

5. (*a*) What kind of an electric charge has the electron? (*b*) Making use of the electron theory, account for the charge on hard rubber when rubbed with wool or cat's fur.

6. (*a*) Mention the essential parts of a condenser. (*b*) Mention one practical use of the condenser.

7. Mention (*a*) three respects in which the behavior of magnets is similar to that of electric charges; (*b*) two respects in which it is different.

8. A charged body when brought near a suspended pith ball will first attract it, and then repel it. Explain.

9. Large sparks can frequently be seen jumping from leather belts which are driving machinery. Explain.

10. An ebonite rod rubbed with fur will attract the fur with which it is rubbed. Explain.

THREE— CELLS AND BATTERIES

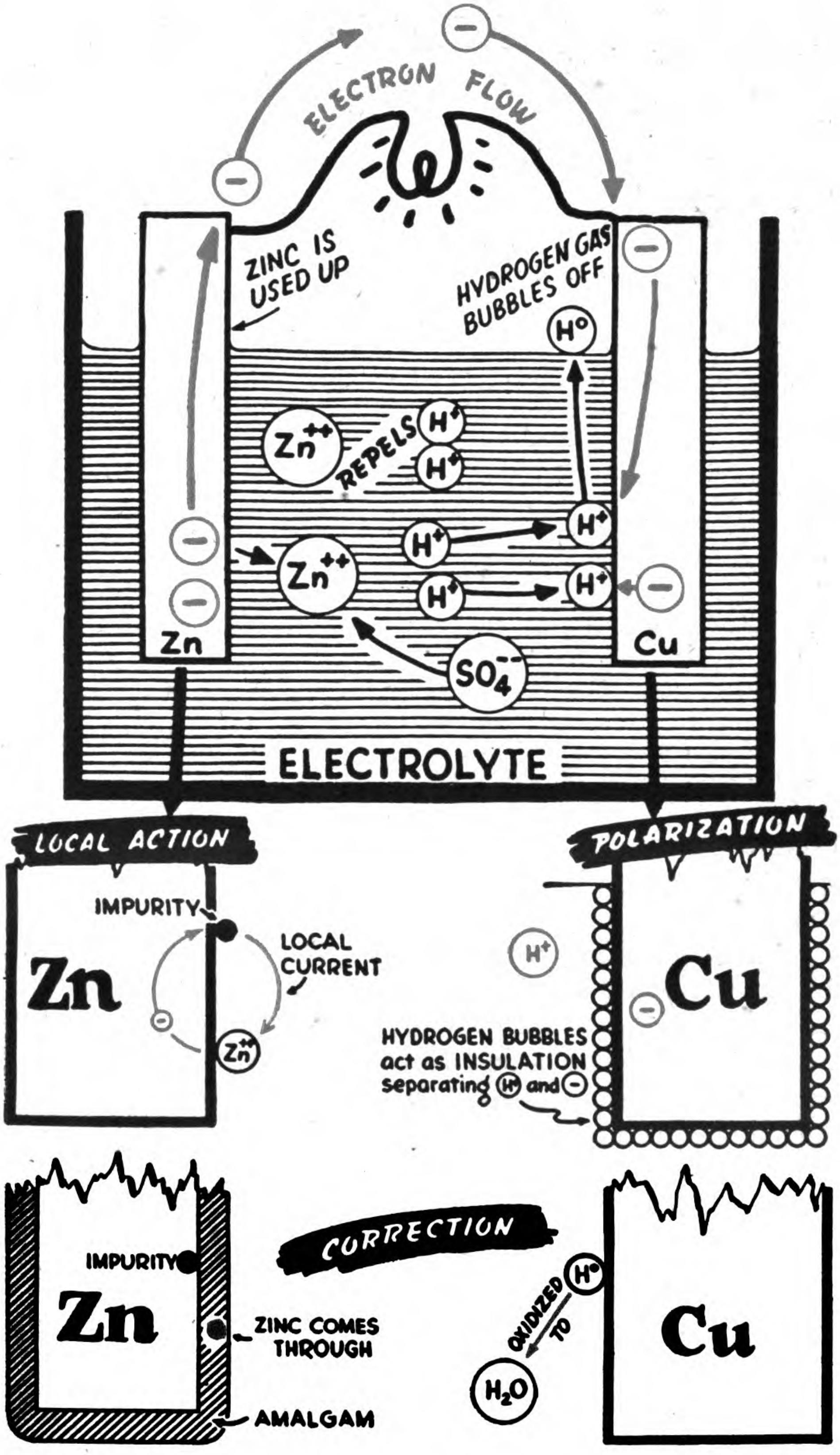
THE PRIMARY CELL

Importance of Difference in Potential. As we have seen, electrons flow from one point to another only when there is a difference in potential between the two points. In order to maintain a continuous flow of electrons (current of electricity), there must be a continuous difference of potential. The marvels of our present electrical age were made possible as a result of the discovery and development of two ways to maintain a constant difference in potential: (1) by chemical action in cells and batteries; (2) by mechanical generators (discussed in chapter 7). The first chemical cell that successfully delivered a continuous current of electricity was devised by the Italian physicist, Volta, and announced in the year 1800. Simple chemical cells are called *voltaic* cells in his honor. Voltaic cells depend upon *ionization* for their operation.

Ionization. The hydrogen atom is neutral because the negative electron balances the positive charge of the proton in the nucleus. If the electron were removed, a positively charged hydrogen *ion* would remain. *Ions are electrically charged atoms or groups of atoms.* Acids, bases, and salts, when they are dissolved in water, break up into ions, which wander about (migrate) freely in the solution. This process is called *dissociation* and the solution containing ions is called an *electrolyte.*

Chemical Action Within a Voltaic Cell. The essential parts of the voltaic cell are: (1) two dissimilar *electrodes* composed, usually, of two unlike metals or a metal and carbon; (2) an *electrolyte.* A simple cell for experimental study can be made by immersing strips of zinc and copper in a water solution of sulfuric acid. A potential difference of 1.10 volts is generated.

When sulfuric acid, $H_2(SO_4)$, is put into solution, it separates into two kinds of ions: H^+ and $(SO_4)^{--}$. When the strips of copper and zinc are connected by a wire, action occurs at both electrodes.



Action in a Voltaic Cell, and Correction of Its Defects

1. Atoms of zinc break away from the zinc strip and go into solution as Zn^{++} ions, each one leaving 2 electrons behind it on the strip. These electrons make this electrode negative, and repel other electrons along the connecting wire toward the copper.

2. The Zn^{++} ions that enter the solution repel many of the H^+ ions through the solution toward the copper strip. The H^+ ions gain electrons at the copper strip, and thus tend to leave it deficient of electrons, that is, with a positive charge. Since the copper is connected to the negatively charged zinc strip, electrons are attracted from the zinc to the copper along the conducting path. As the H^+ ions gain electrons, they form neutral hydrogen gas which bubbles up around the copper electrode.

*This flow of electrons constitutes an electric current.** Such a chemical cell continues to transform chemical energy into electrical energy until either the zinc or the H^+ ions are exhausted.

Characteristics and Defects of Voltaic Cells. Experiments have shown that *the voltage of a cell depends only on the composition of electrodes and electrolyte.* The voltage is not affected by the distance between the plates, or the area of the plates in contact with the electrolyte, or the size of the cell. These latter factors do, however, affect the *amount of current* the cell can deliver and also the *length of time* it will last.

Local action. Impurities in commercial zinc act as positive electrodes and form little, local cells with the zinc atoms when they come into contact with the electrolyte. Thus, the ionization of the zinc is speeded up, but the energy released by this *local action* is not delivered to the outside circuit, and hence is wasted. The remedy for local action consists of coating the zinc with mercury, a treatment called *amalgamation.* The zinc is soluble in the mercury and finds its way to the surface, where it can react with the acid; but the impurities, being insoluble in the mercury, remain submerged and out of contact with the acid.

Polarization. In any cell in which hydrogen is formed during use, tiny bubbles of this gas tend to collect on the surface of the

---

* Years before scientists knew anything about electrons, it was agreed to consider the electric current as flowing from positive (+) to negative (−). We now know that the actual direction of flow (of electrons) is from negative to positive. In spite of this newer knowledge, however, the older terminology is still used. Hence, we are merely being conventional when we say that the electric current flows from plus to minus.

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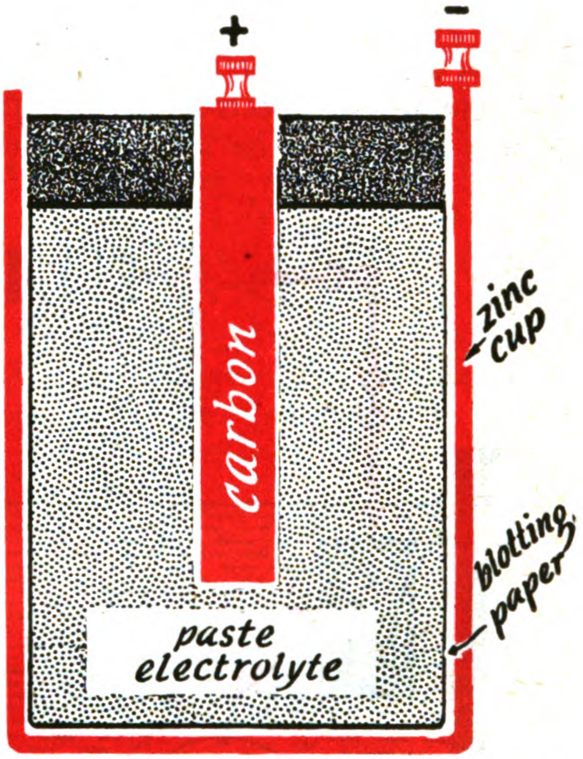
positive plate. This layer of gas acts as an insulator and offers increased resistance to the transfer of electrons, thus causing the current to decrease. The effect is termed *polarization.* If manganese dioxide is added to the electrolyte solution in the copper-zinc-sulfuric acid cell, polarization is overcome by the oxidizing action of this chemical; it converts the hydrogen into water about as fast as the gas is formed.

The Dry Cell. The term "dry cell" is somewhat misleading since the cell is not really dry. Instead of a liquid electrolyte solution, the active chemical is in paste form. Actually, the cell is sealed so that externally it is dry. The negative plate of the cell is a zinc cup. A carbon rod placed at the center of the cell serves as the positive electrode. The zinc cup is lined with blotting paper soaked in ammonium chloride solution, and the space between it and the carbon rod is filled with ammonium chloride, manganese dioxide, and granulated carbon, all mixed to form a paste. The manganese dioxide serves as the depolarizer. The cell generates about 1.5 volts on open circuit. It is termed a *primary cell,* because once the chemicals are used up, it cannot be recharged but must be replaced by a new cell. (See page 56 for cell circuits.)



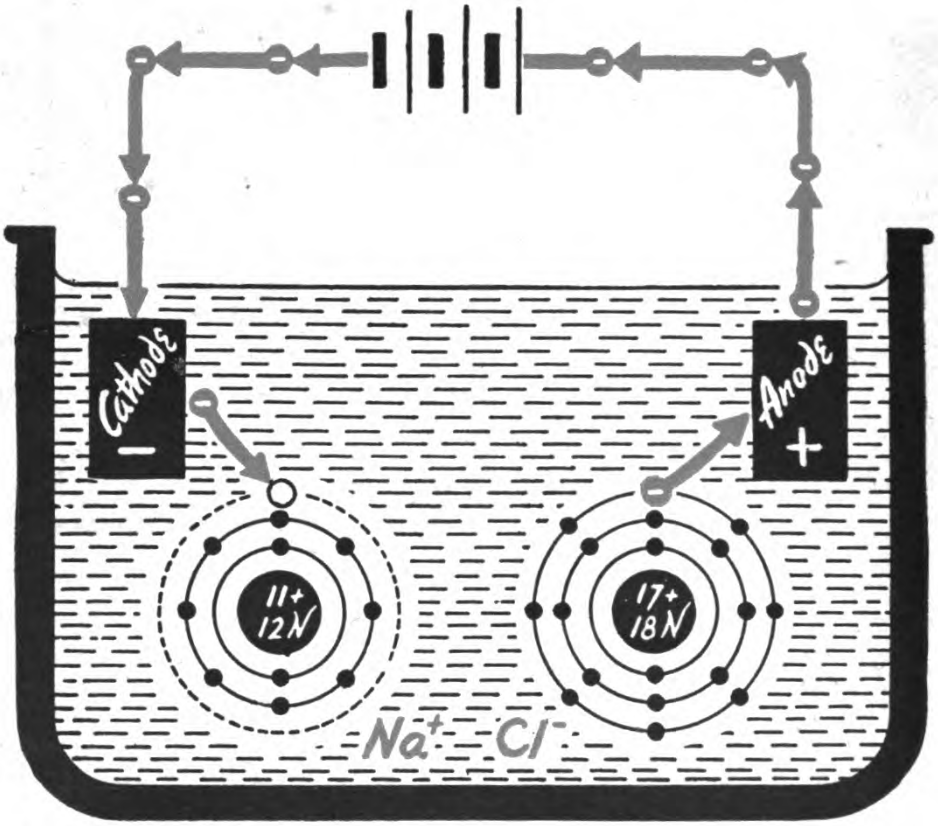
The Dry Cell. The electrodes are shown in red.

CHEMICAL EFFECTS OF AN ELECTRIC CURRENT

Up to now, we have considered how chemical action produces an electric current. We shall now see how a current produces chemical action.

Electrochemistry. Several important chemical industries are founded on chemical changes that take place when an electric current is passed into certain conducting solutions. These *electrochemical* industries supply some of the most vital materials our country needs today, such as chlorine, sodium hydroxide, metallic sodium, aluminum, calcium, magnesium, etc. In addition, *electrolysis* (chemical change brought about by electricity) is applied in electroplating, the refining of copper, the storage battery, and other processes. Certain fundamental *laws of electrolysis* govern all these electrochemical effects.

Principles of Electrolysis. In our discussion of the voltaic cell, it was seen how the ions in an electrolyte generate an electric



Electrolysis of Sodium Chloride. The positive sodium ion is attracted to the cathode, where it gains an electron and thus becomes neutral. The negative chlorine ion is attracted to the anode, where it gives up an electron and thus becomes neutral. For each electron given up by the cathode, one is gained by the anode. The electron flow is shown in red.

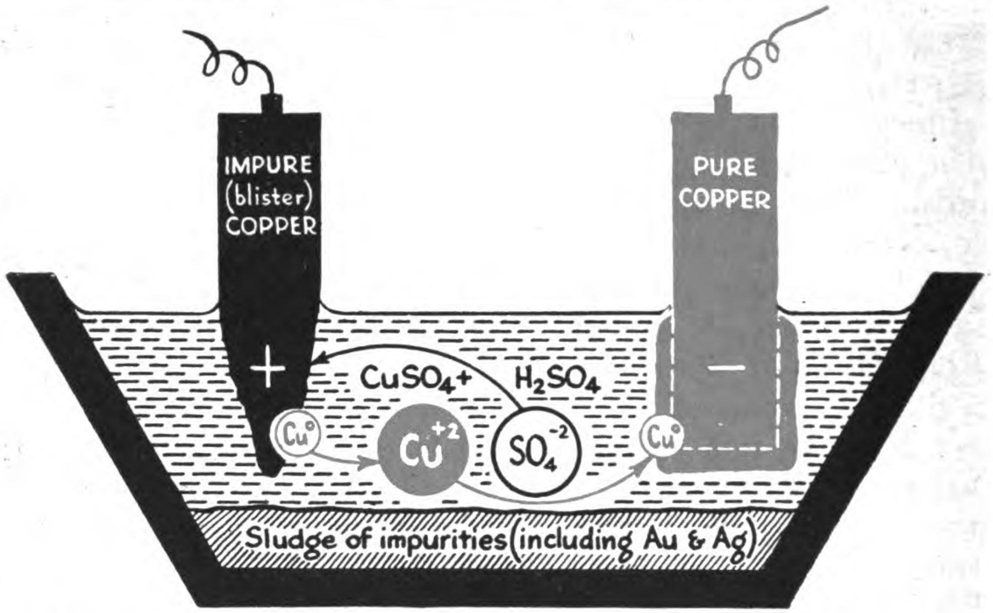
current. Electrolysis is substantially the action of a voltaic cell in reverse. In electrolysis, two electrodes connected to a source of direct current (DC) are inserted in an electrolyte. The ions in the electrolyte respond to the law of electrical attraction and repulsion; that is, the positive ions migrate toward the negative pole, or *cathode,* and the negative ions migrate toward the positive pole, or *anode.* A typical electrolytic action is shown in the diagram on page 34.

Electrolysis of Water. The electrolysis of water is carried out in a similar manner. A little sulfuric acid is generally added to the water to make it a conductor. When current is passed into the solution, oxygen collects at the positive pole and hydrogen collects at the negative pole. The volume of hydrogen is twice the volume of the oxygen.

Electroplating. Electroplating is essentially the act of putting a thin coating of one metal on the surface of another by means of electrolysis. The purpose is usually to make the plated object more resistant to corrosion, or to simulate the appearance of a more costly article (silverplated ware, for example). The object to be plated is thoroughly cleansed and is attached to the cathode. A bar of the pure plating metal (nickel, cadmium, silver, chromium, etc.) is attached to the anode. The solution contains a dissolved salt of the plating metal.

The refining of copper is also accomplished by electroplating. The action is explained in the diagram on page 36.

Laws of Electrolysis. Michael Faraday conducted experimental studies which led him to formulate *three laws of electrolysis,* as follows. The amount of metal deposited by electrolysis is directly proportional to (1) *the length of time the current flows;* (2) *the strength of the current in amperes;* and (3) *the electrochemical equivalent of the metal.* By definition, the electrochemical equivalent of an element is the *weight in grams* of that element which deposits from solution when a current of *1 ampere* flows for *1 second.* For example, if 3.354 g of silver are deposited by a current of 10 amperes in 5 min, then 1 ampere would deposit 0.3354 g in 5 min (300 sec), and 1 ampere would deposit 0.001118 g in 1 sec; thus the electrochemical equivalent of silver is 0.001118 g. This value can be determined so accurately that it is used in calibrating ammeters and is the basis of the *standard international ampere.*



Refining of Copper. The positive copper ions in the solution are attracted to the cathode, become neutral, and deposited as pure, metallic copper. Simultaneously, copper atoms leave the anode and enter the solution as copper ions. All electroplating operates on this principle. Pure metal is deposited on the cathode (object to be plated); the anode is made of the plating metal.

THE SECONDARY CELL

The Lead-Acid Storage Battery. Storage batteries consist of two or more secondary cells, that is, cells which can be discharged and recharged repeatedly. The active material on the positive electrode of the lead-acid cell is lead peroxide (PbO_2); the negative electrode consists of spongy lead. The electrolyte is a dilute sulfuric acid solution.

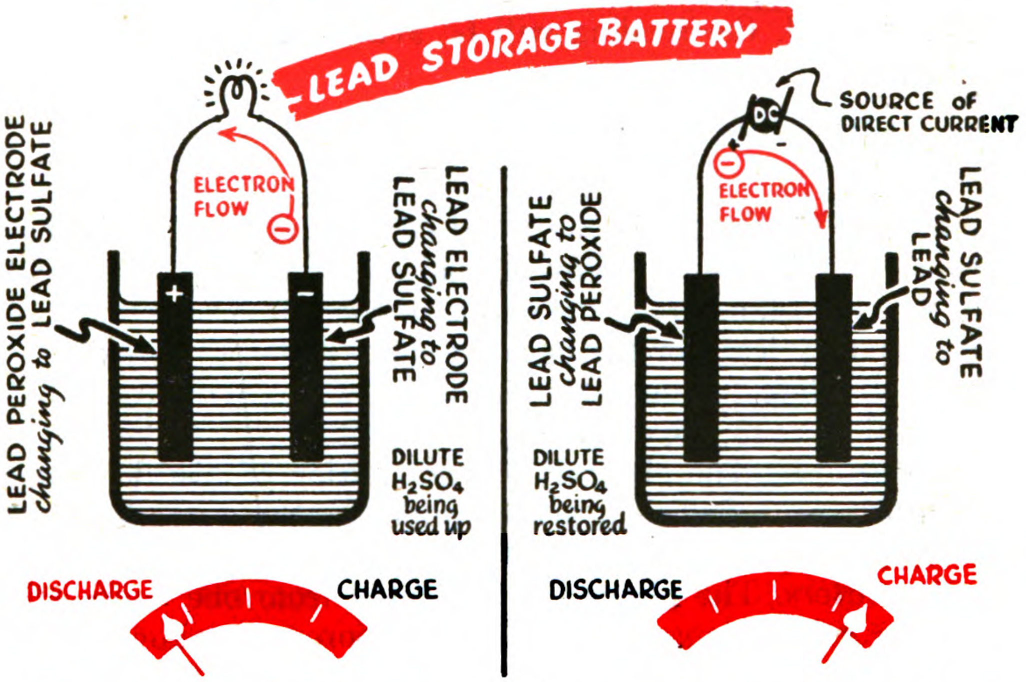
When the battery is charged, it contains stored *chemical energy*. This energy is transformed into *electrical energy* by the reactions that ensue when the terminals of the cell are connected; that is, when the cell is discharging.

On discharge, hydrogen ions of the sulfuric acid remove oxygen from the lead peroxide electrode and unite with them to form water. The electrode is reduced to lead, which then combines with sulfate ions to form a deposit of lead sulfate. These reactions give this electrode a positive charge. At the other electrode, lead atoms unite with sulfate ions to form a deposit of lead sulfate. By this action, the electrode acquires a negative charge.

When discharging, (1) the cell delivers current to the outside; (2) sulfuric acid is removed from the solution, thus decreasing the specific gravity of the electrolyte; (3) the electrodes gradually become similar in composition, both being coated with lead sulfate; (4) the voltage of the cell drops to less than 2 volts.

When the positive terminal of a charging outfit is connected to the positive terminal of the cell (and negative is connected to negative), current is forced through the cell. To accomplish this, the voltage of the charging current must be higher than the voltage of the cell or battery being charged. Under these conditions, (1) acid is restored to the solution and the specific gravity (specific weight) increases; (2) the electrodes again become dissimilar, the positive becoming lead peroxide and the negative spongy lead; (3) the voltage rises to about 2.2 volts when the cell is fully charged.

The condition of charge of a lead-acid storage battery is best determined by using a hydrometer to test the specific gravity of


LEAD STORAGE BATTERY
LEAD PEROXIDE ELECTRODE *changing to* LEAD SULFATE
ELECTRON FLOW
+
−
LEAD ELECTRODE *changing to* LEAD SULFATE
DILUTE H_2SO_4 being used up
DISCHARGE
CHARGE
SOURCE OF DIRECT CURRENT
DC
LEAD SULFATE *changing to* LEAD PEROXIDE
ELECTRON FLOW
LEAD SULFATE *changing to* LEAD
DILUTE H_2SO_4 being restored
DISCHARGE
CHARGE

When the storage battery is discharging, its action is that of the voltaic cell. When it is being charged, the action is that of electrolysis.

the electrolyte solution. A voltmeter is of little value for testing this kind of battery since it may show a high terminal voltage and yet the battery may not be fully charged. The hydrometer indicates the quantity of sulfuric acid present by indicating the specific gravity (or specific weight) of the electrolyte.

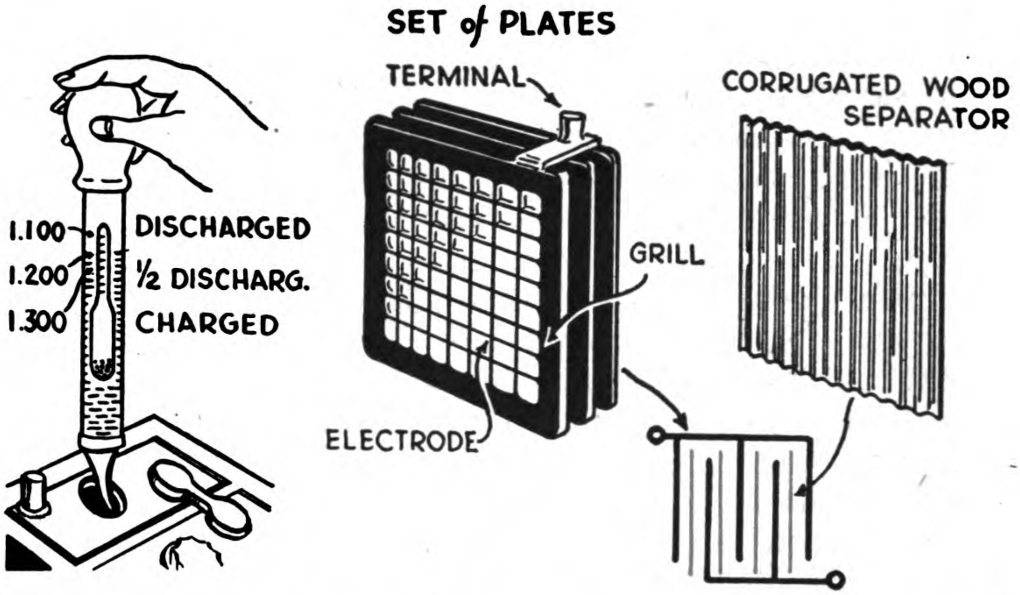
The specific gravity of a substance is the comparative weight of a given volume of a substance with respect to the weight of an equal volume of pure water. For example, the specific gravity of aluminum is 2.7; that is, aluminum weighs 2.7 times as much as an equal volume of water. The specific gravity of pure water is **1**.

The hydrometer is a hollow glass tube weighted with enough lead shot to make it float upright so that its stem is out of the liquid. The stem is calibrated so that the specific gravity of a liquid can be read directly from a scale.

The specific gravity of a fully-charged lead-acid cell is about 1.3. The specific gravity is greater than that of water because sulfuric acid is denser than water. A lower reading means that some of the acid has been used up. When completely discharged, the specific gravity of the electrolyte of the lead-acid battery falls to about 1.1 (1100 on the hydrometer). If the cell is about half discharged, the reading will be about 1.2.

CONSTRUCTION OF THE COMMERCIAL LEAD STORAGE BATTERY

1. *Plates.* The plates in the usual storage battery consist of a grillwork or frame of an alloy of lead and antimony. This grillwork does not take part in the action of the cell. The actual electrodes—spongy lead for the negative plate and lead peroxide for the positive plate—are inserted in the grillwork. A three-cell battery usually has 13, 15, or 17 plates.
2. *Electrolyte.* The electrolyte is a solution of distilled water and sulfuric acid. Sufficient acid is added to the water to give a specific gravity reading of 1.300 before use.
3. *Separators.* The plates are separated from one another by wooden or rubber separators. These are porous to allow for circulation of the electrolyte.
4. *Case.* The outside container is composed of a material (usually hard rubber) that will resist the action of the chemicals and prevent any leakage of the electrolyte.



The Lead Storage Cell. A single set of plates (positive or negative) is illustrated. When interleaved with a set of plates of opposite polarity, and immersed in sulfuric acid solution, a single cell is formed. Several cells comprise a battery. The condition of the battery is tested by measuring the specific gravity of the acid with a hydrometer.

5. Arrangement within battery. All the positive (lead peroxide) plates within a cell are connected to one outside terminal and all the negative (lead) plates are connected to another terminal.

Care of the Battery. The most important thing to remember about the care of the storage battery is not to overcharge or over-discharge it. Overcharging may cause an excessive deposit of lead peroxide on the positive plates, which in turn may cause them to buckle. Over-discharging results in the excessive deposit of lead sulfate on the surface of all the plates, causing them to expand and buckle. The lead sulfate sometimes chips off and falls to the bottom of the cell, forming a sediment. Over-discharging may also cause the separators to become clogged. Broken plates, clogged separators, and excessive sedimentation at the bottom of the cell may short circuit the cell.

The water from the electrolyte evaporates upon standing. This water must be replaced from time to time. Pure distilled water should be used, since ordinary tap water, while perfectly healthy for drinking purposes, contains mineral ingredients which may short circuit the plates in the cell.

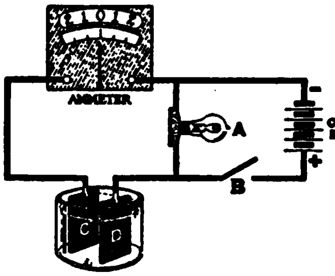
Capacity of the Lead-Acid Battery. The capacity of a storage battery is measured in *ampere-hours*. This means that a 50 ampere-hour battery can supply one ampere for 50 hours, 50 amperes for one hour, or any combination of amperes and hours whose product is 50. Battery manufacturers, however, usually state the maximum amperage that can be safely drawn without damaging the battery. The capacity of a battery depends upon the size and the number of plates. The larger the area of the plates exposed to the electrolyte the greater is the capacity of the battery.

The usual lead-acid cell generates about 2 volts. A battery of 2, 3, or 6 cells in series gives approximately 4, 6, or 12 volts. The common automobile battery has three cells, while an Army airplane battery contains 6 cells, and is designed so that the electrolyte will not spill even if the airplane turns upside down. (For cell connections in series and in parallel, see page 57.)

Lead-acid storage batteries are used for ignition and lighting on automobiles and airplanes; they drive the electric motors of submerged submarines; large ones serve as reservoirs of electrical power for emergency use in hospitals, telephone exchanges, etc.; and they have dozens of other miscellaneous uses.

BEST ANSWER TEST

1. The accompanying diagram represents the arrangement of apparatus to show the charging and discharging of a simple lead storage cell. *A* is a small lamp which is screwed out of the socket during charging and screwed in again during discharging. *B* is a switch which is opened during the discharging. Referring to the diagram, complete the following statements:



(*a*) *C* is the (positive, negative) plate of the storage cell.

(*b*) The chemical compound on plate D after charging is called ________.

(*c*) The electrolyte of the cell is a solution of ________ acid in water.

(*d*) The amount of water in the cell during the charging process (increases, decreases, remains the same).

(*e*) During discharge, the plates tend to become (alike, unlike).

(*f*) The charging current flows into the cell at (the same pole at which, the opposite pole from which) the discharged current flows out of the cell.

2. The electrolyte in the ordinary dry cell is (zinc, carbon, manganese dioxide, ammonium chloride, sulfuric acid).

3. In the ordinary dry cell, polarization is overcome by the action (of the zinc, of the carbon, of the ammonium chloride, of the manganese dioxide, known as amalgamation.)

4. A storage battery really stores (electrical energy, chemical energy).

5. The amount of metal deposited in electroplating is proportional to the _____, the _____, and the _____.

QUESTIONS

1. Why will a dry cell deliver a small current for a fairly long time without polarization, but not a large current?

2. What is the source of energy delivered by the dry cell?

3. Distinguish between local action and polarization.

4. Make a labeled diagram to explain the electrolysis of water.

5. How would you go about plating a brass object with chromium? What kind of current would you need? Why?

6. Decide whether each of the following statements is true or false and give a reason for your answer.

(*a*) The plates of a discharged storage battery are coated with lead sulfate.

(*b*) During the electrolysis of water, hydrogen collects at the cathode.

(*c*) The object to be plated is attached to the anode.

(*d*) The weight of silver that deposits during electroplating depends on the amperage and the time.

7. State Faraday's laws of electrolysis.

8. Make a labeled diagram for an apparatus that could be used for electroplating.

FOUR— VOLTAGE, CURRENT, RESISTANCE; THE ELECTRIC CIRCUIT

FUNDAMENTALS OF THE ELECTRIC CIRCUIT

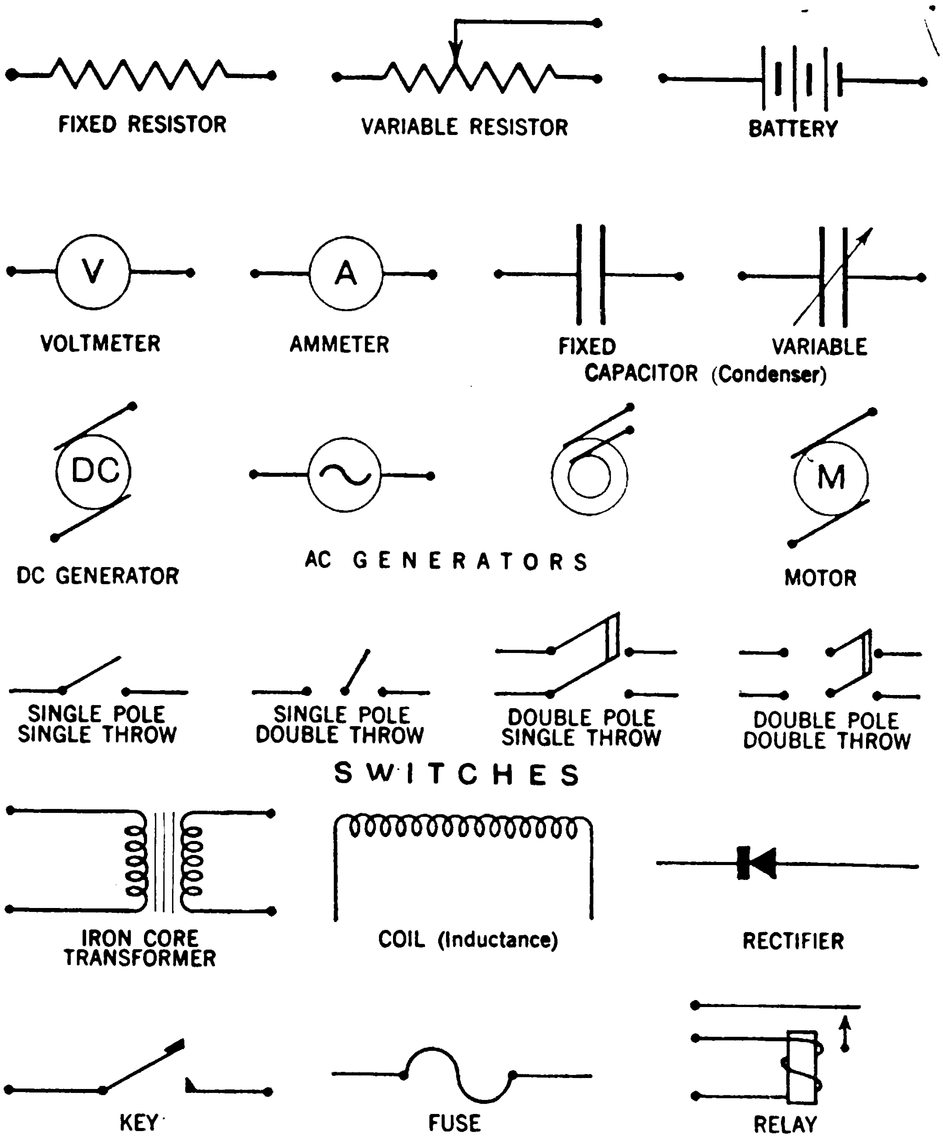
Electric Current. As stated on page 19, a flow of electrons from one point to another is an *electric current.* In this and the following chapters of this book, we shall study the various effects and laws of electrons in motion, or current electricity.

The Direct Current Circuit. As we shall see later, there are two main kinds of electric currents. In one case, the electrons flow continuously in the same direction; this is called a *direct current.* In the other case, the electrons repeatedly change direction, flowing one way at one instant, and flowing the other way a little later; this is called an *alternating current.* In this chapter we will study the laws of direct currents.

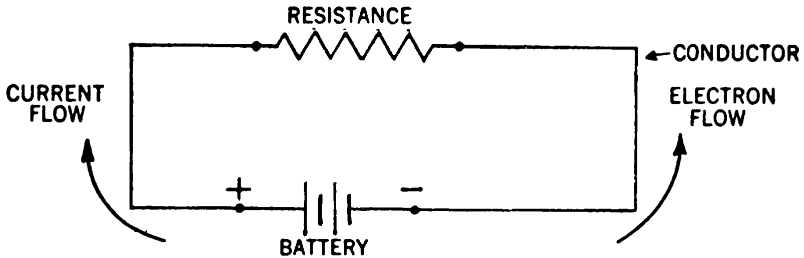
A direct current *circuit* is any unbroken conducting path along which electrons may flow. It usually contains a battery or other generator for producing a flow of electrons, as well as one or more conductors connecting the terminals of the generator. In the circuit there may be several electrical devices, such as lamps, motors, toasters, or coils of wire, each of which tends to impede the flow of electrons to some extent, and is hence called a *resistance* (or *resistor*). The circuit may also contain *meters* which measure current, emf, or other electrical quantities.

A circuit is said to be *open* when there is a break or gap in it so that no current can flow. Circuits often contain switches which are used to open and close the circuit. The diagram on the next page shows the common symbols used in schematic diagrams of electric circuits as well as the diagram of a simple circuit containing a battery and a single resistance. The straight lines connecting the resistance to the battery are connections which are assumed to have no resistance to the flow of current; in actual circuits, these would be the wires used to connect various devices together.

SCHEMATIC ELECTRIC SYMBOLS



SIMPLE CIRCUIT



Electrical Units of Measurement. There are three basic measurements made in electrical circuits: (1) magnitude of current flow; (2) potential difference between two points in a circuit; (3) resistance of a circuit element. These measurements are based on the following electrical quantities or units.

The coulomb. The coulomb is a unit of measurement of quantity of electricity—in other words, number of electrons. One coulomb is equal to a certain number of electrons (6,300,000,000,000,000,000), just as the liter is a certain number of cubic centimeters. The coulomb has nothing to do with current *flow*—it is a unit of static electricity.

The ampere. The ampere is the unit of measurement of current flow, and is equal to a rate of flow of *one coulomb per second.* In other words, if you could count the electrons passing along a conductor, and you found that one coulomb (6,300,000,000,000,000,000 electrons) went by in one second, then you would know that there was a current of one ampere flowing in that conductor. If *3* coulombs went by in one second, then there would be a current of *3* amperes flowing.

Actually it is possible to count electrons as they flow through a circuit; it is done by electrolysis of a silver nitrate solution. It has been found that one coulomb of electricity flowing through a silver nitrate solution always deposits 0.001118 grams of silver. Therefore, if a current deposits this weight of silver (0.001118 g) *in one second,* there is one coulomb flowing through each second, or a current of *one ampere.* The standard ampere used to calibrate ammeters is determined by just such an electrolysis experiment.

A current under ½ ampere is considered to be a low current; most current values in radio circuits are in this range. A current between ½ ampere and 6 amperes is considered to be a medium-sized current; these are frequent in home appliances such as toasters, refrigerators, lamps, etc. A current over 6 amperes is a high current; these occur in industrial applications, power stations, and power transmission lines. Since a current of 6 amperes is considered large, we see that the ampere is itself a large unit.

The volt. A potential difference is needed to force electrons to move along a conductor from one point to another; the volt is the unit of measurement of this electrical pressure, or "push" behind the electrons. The standard volt is determined by means of a voltaic cell made according to definite specifications. This standard cell is called a Weston cell. Voltages under 50 volts are considered low; 50 to 220 volts, medium; above 220 volts, high.

The ohm. The ohm is the unit of measurement of resistance to current flow. A conductor has a resistance of one ohm if it requires one volt to force a current of one ampere through it. In other words, the resistance of a conductor (in ohms) indicates how large a voltage is needed to produce a given current in the conductor. The exact relationship between ohms, volts, and amperes is called Ohm's law, discussed below.

Practical Units. There are frequent instances where the fundamental units are either so large or so small that very large numbers must be used, thus becoming too cumbersome to be practical. Just as we use millimeters, meters, and kilometers for various distances, so we use a system of prefixes to designate electrical quantities of various magnitudes. Four such prefixes are in common use. They are listed below, together with their relation to the fundamental unit:

$$\left.\begin{array}{l}\text{Micro-, } 0.000001 \text{ or } 10^{-6}\\ \text{Milli-, } 0.001 \text{ or } 10^{-3}\\ \text{Kilo-, } 1000 \text{ or } 10^{3}\\ \text{Meg-, } 1{,}000{,}000 \text{ or } 10^{6}\end{array}\right\}\text{ times the fundamental unit}$$

Thus, a milliampere is one one-thousandth of an ampere; a microvolt is one one-millionth of a volt; a megohm is one million ohms. These units are commonly used in radio.

Factors Affecting Resistance. Since most electrical conductors are fabricated in the form of wire, and electrical circuits and appliances make use of wire, the *laws of resistance* are generally stated as follows.

1. *Composition determines resistance.* The resistance of iron wire, for example, is about 7 times as much as the resistance of copper wire of the same diameter and length.

2. *Resistance is directly proportional to length.* A wire 10 feet long offers twice as much resistance as 5 feet of the same wire.

3. *Resistance is inversely proportional to cross-section area.* A wire three times the diameter of another wire having the same length and composition, offers only one-ninth the resistance; it has nine times the cross-section area (since area varies with the

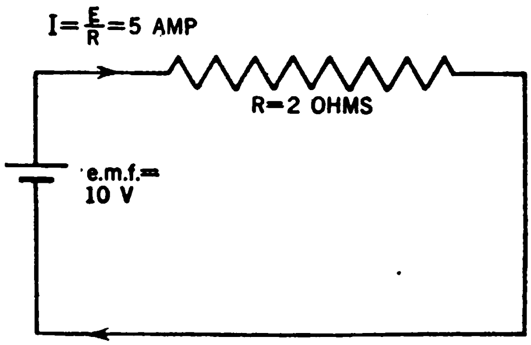
square of the diameter), and it is nine times as easy for a given current to flow through it.

These laws of resistance are expressed by the formula,

$$R = \frac{kl}{d^2}$$

in which R = the resistance in ohms, l = the length in feet, d = the diameter in mils (1 mil = .001 in), and k = a constant depending for its value on the material used.

4. *Temperature affects resistance.* All conductors undergo changes of resistance with changes in temperature. In general, the resistance of a metal increases with a rise of temperature, while the resistance of most liquid and non-metallic conductors (carbon) decreases as the temperature rises.



An Illustration of Ohm's Law

Ohm's Law. Ohm's law is a formula which tells us what current will flow in a circuit when we know the voltage and the resistance. It is based on the following two facts discovered by the German physicist, Ohm: (1) the current in a circuit is directly proportional to the voltage—doubling the voltage doubles the current; (2) the current is inversely proportional to the resistance—doubling the resistance reduces the current by half. Expressed as a formula:

$$\text{current} = \frac{\text{voltage}}{\text{resistance}}$$

$$I = \frac{E}{R}$$

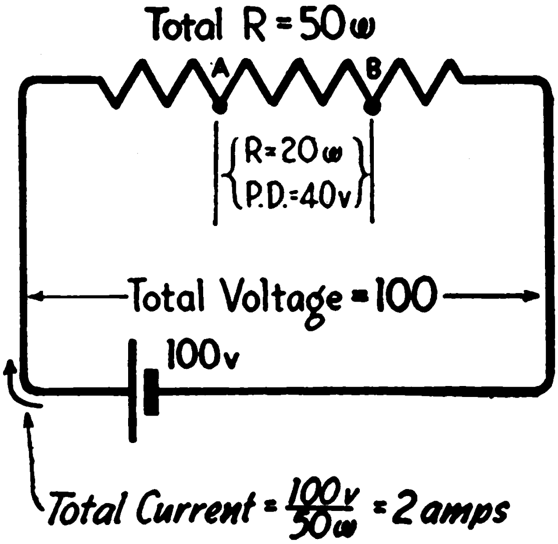
The letter I stands for current in amperes ("I" is the initial letter of "intensity" of current); E represents voltage or *e*lectromotive force; R stands for *r*esistance in ohms.

Voltage Drop. Although we have spoken of voltage as an electrical pressure *behind* the electrons, it is incorrect to think of this pressure as concentrated at one point or at one end of a circuit. Voltage is always a *difference* of potential *between* two points.

In the case of an entire circuit connected to a battery, the potential difference or voltage across the circuit is the emf of the battery. This total voltage causes the flow of current in the circuit.

However, each section of the circuit has its own voltage causing current to flow through that section. In other words, there is a potential difference between *any* two points in a circuit (not only the two ends); it is this potential difference which produces current *between those two points*. This difference of potential between two points in a circuit is called the *voltage drop* between the points.

The voltage drop anywhere in a circuit obeys Ohm's law. If the voltage drop between any two points is divided by the resistance of the circuit between those points, the result will be the current flowing through the circuit at those points.



Voltage Drop. The total voltage across the resistance of 50 ohms is 100 volts, producing a current of 2 amperes. The portion of the circuit between A and B has a resistance of only 20 ohms. Therefore, by Ohm's law, the voltage drop between points A and B, is $E = IR = 2 \times 20 = 40$ volts. A voltmeter connected between A and B would read 40 volts.

TYPICAL PROBLEMS

An incandescent lamp has a resistance of 220 ohms when hot. Find the current through the lamp when it is operated on a 110-volt line.

$$R = 220 \text{ ohms};\ E = 110 \text{ volts};\ I = ?$$

$$I = \frac{E}{R},\ \text{or } I = \frac{110}{220} = \mathbf{0.5\ ampere}$$

An electric toaster operating on 120 volts emf draws a current of 6 amperes. What is the resistance of the coil of the toaster?

$$E = 120 \text{ volts};\ I = 6 \text{ amperes};\ R = ?$$

$$R = \frac{E}{I},\ \text{or } R = \frac{120}{6} = \mathbf{20\ ohms}$$

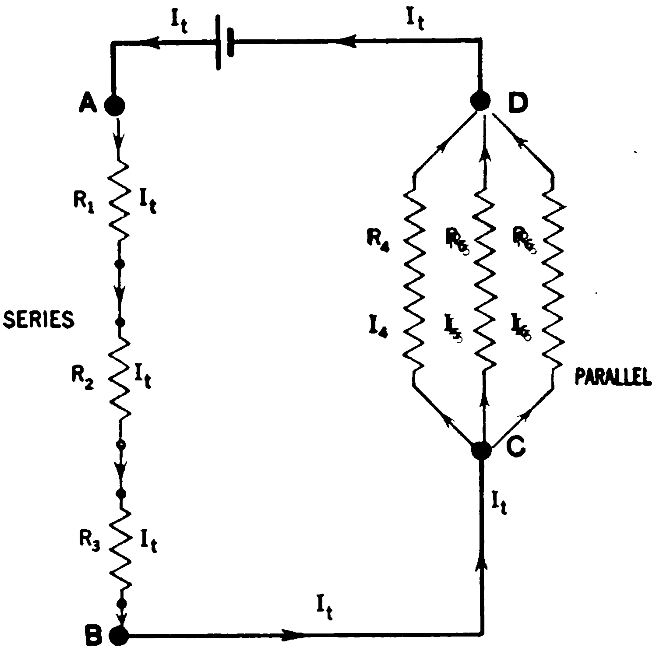
What emf is necessary to produce a current of 0.02 ampere through a resistance of 5000 ohms?

$$E = ?;\ I = 0.02 \text{ ampere};\ R = 5000 \text{ ohms}$$
$$E = IR, \text{ or } E = 0.02 \times 5000 = 100 \text{ volts}$$

The voltage drop across a 1.5 megohm radio resistor is 30 volts. What current (in milliamperes) flows through it?

$$E = 30 \text{ volts};\ R = 1.5 \times 10^6 \text{ ohms};\ I = ? \text{ milliamps}$$
$$I = \frac{E}{R}, \text{ or } I = \frac{30}{1.5 \times 10^6} = 20 \times 10^{-6} \text{amp} = 20 \times 10^{-3} \text{milliamp}$$
$$= 0.02 \text{ milliamp}$$

SERIES AND PARALLEL CIRCUITS



Resistances in Series and in Parallel

The Series Connection. If two or more resistances are connected in such a way that the current flows through each of them *in turn,* they are said to be *in series.* In a series circuit, the current which flows through one resistance must flow through the next, and the next, etc. The current stops if the circuit is broken at any point.

The Parallel Connection. If two or more resistances are connected so that the current *divides* when it reaches them, part going through one, part through another, etc., and then recombines upon leaving the resistances, the resistances are said to be *in parallel.* Any branch of a parallel circuit may be broken without stopping the current flow in the other branches. An important characteristic of the parallel connection is that each branch has the same voltage drop.

Characteristics of a Series Circuit.

1. *The current is the same throughout a series circuit.* There can be no loss or gain of current (electrons); hence, all of the electrons that flow out of the generator or battery must flow through the circuit and return. A break anywhere in a series circuit completely stops the flow of current.

$$I_1 = I_2 = I_3, \text{ etc.}$$

2. *The total or equivalent resistance (R_{eq}) of a number of resistors in series is the sum of their separate resistances.*

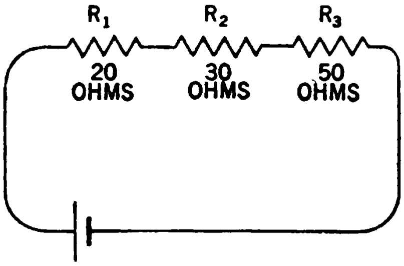
$$R_{eq} = R_1 + R_2 + R_3, \text{ etc.}$$

3. *The total voltage drop across a number of resistors in series is the sum of the voltage drops across the individual resistors.*

$$E_t = E_1 + E_2 + E_3, \text{ etc.}$$

TYPICAL PROBLEM

Three resistors of 20 ohms, 30 ohms, and 50 ohms respectively are connected in series. The current through R_1 (20 ohms) is 0.8 ampere. (*a*) What is the current through R_3 (50 ohms)? (*b*) What is the voltage across R_2? (*c*) What is the total voltage drop across the three resistors?



(*a*) In a series circuit, $I_1 = I_2 = I_3$, etc. $I_1 = 0.8$ ampere; hence
$I_3 =$ **0.8 ampere**

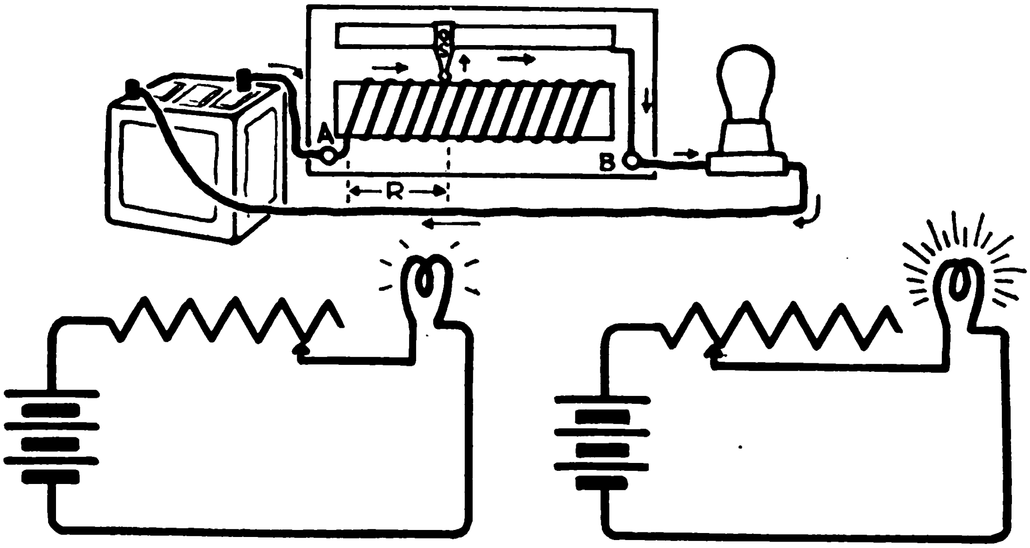
(*b*) $I_2 = 0.8$ ampere; $R_2 = 30$ ohms; $E = ?$
$E = IR$, or $E = 0.8 \times 30 =$ **24 volts**

(*c*) In a series circuit, $E_t = E_1 + E_2 + E_3$, etc.
$E_1 = IR_1$, or $E_1 = 0.8 \times 20 =$ *16 volts*
$E_3 = IR_3$, or $E_3 = 0.8 \times 50 =$ *40 volts*
$E_t = 16$ volts $+ 24$ volts $+ 40$ volts $=$ **80 volts**

or

$E_t = IR_{eq}$, or $E_t = I(R_1 + R_2 + R_3)$;
Hence, $E_t = 0.8 \times (20 + 30 + 50) =$ **80 volts**

The Rheostat. It is often necessary to control the amount of current flowing in a circuit. This could be done by changing the voltage, but in many cases this isn't practical. For example, you cannot alter the voltage at the electrical outlets in your home; and you cannot change the voltage supplied by a dry cell. In such cases, the current can be changed by changing the total resistance of the circuit. A rheostat is a variable resistance used for this purpose. It consists of a large number of turns of resistance wire mounted on an insulator. One terminal of the device is connected to one end of this coil of wire; the other terminal is connected to a metal slider which can be moved along the coil. The device is connected in series with the rest of the circuit. As the slider is moved away from the connected end of the coil, more and more resistance is added to the circuit, thus reducing the current; the current is increased by moving the slider back toward the connected end.



The Rheostat. The portion of the coil between the terminal A and the slider S (the part labeled R) is in the circuit. As the slider is moved toward the terminal A, the total circuit resistance is reduced, more current flows, and the lamp becomes brighter.

Characteristics of Parallel Circuits. In a parallel circuit, the main-line current divides and flows simultaneously through the various branches. The type of circuit used in wiring our homes illustrates a parallel circuit. Each appliance is really connected separately across the main line. Series wiring cannot be used in homes because the total resistance of two or three ordinary lamps would be sufficient to prevent the flow of enough current from a 120-volt line to light them fully. Furthermore, we would have to use all of the appliances connected in series whenever we wished to use any one of them. Parallel circuits permit independent use of the various branches; a break in one branch of a parallel circuit does not interrupt the flow of current in other complete branches. The characteristics of parallel circuits are as follows.

1. *The total current* (I_t) *flowing in the main line is the sum of the currents in the separate branches.*

$$I_t = I_1 + I_2 + I_3, \text{ etc.}$$

2. *The voltage across each branch of a parallel circuit is the same.*

$$E_1 = E_2 = E_3, \text{ etc.}$$

3. *The main line current divides in a parallel circuit, with the largest fraction of the current going through the branch of least resistance and the smallest fraction going through the branch of largest resistance.* In other words, Ohm's law applies to each branch of a parallel circuit.

$$I_1 = \frac{E}{R_1}; I_2 = \frac{E}{R_2}; I_3 = \frac{E}{R_3}; \text{ etc.}$$

4. *The total or equivalent resistance* (R_{eq}) *of a number of resistors in parallel is less than the resistance of any one of them —even less than that of the separate branch offering the least resistance.* This fact is not difficult to understand if it is remembered that a resistance is a conductor, and each branch may be thought of as another pathway through which additional current flows; hence, as more conductors are added, the equivalent resistance becomes less.

The *conductance* of a device indicates how well it allows current to flow, in contrast to *resistance* which indicates just the opposite. Hence, *conductance* (symbol = G) *is the reciprocal of resistance* (R):

$$G = \frac{1}{R}$$

5. *The total conductance* (G_{eq}) *of a parallel circuit is the sum of the conductances of the separate branches.*

$$G_{eq} = G_1 + G_2 + G_3, \text{ etc.}$$

Substituting in this formula for the value of G, we derive the formula for the equivalent resistance of a parallel circuit:

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}, \text{ etc.}$$

The equivalent resistance of n equal resistors connected in parallel is $\frac{1}{n}$ times the resistance of one of them.

TYPICAL PROBLEMS

What is the equivalent resistance of 20 ohms, 40 ohms, and 80 ohms connected in parallel?

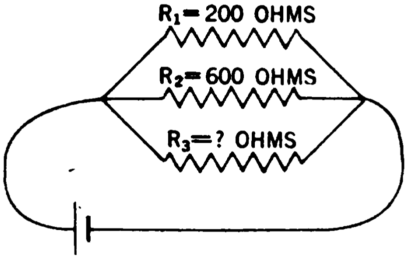
(*Note*: Answer must be less than 20 ohms.)

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}, \text{ or } \frac{1}{R_{eq}} = \frac{1}{20} + \frac{1}{40} + \frac{1}{80}$$

$$80 = 4R_{eq} + 2R_{eq} + R_{eq}$$

$$80 = 7R_{eq}$$

$$R_{eq} = 11.4 \text{ ohms}$$



A resistor of 200 ohms, one of 600 ohms, and one of unknown value are connected in parallel to a source of emf. The voltage across R_1 (200 ohms) is 40 volts. The current in the unknown resistor (R_3) is 0.40 amp. Find (*a*) the value of R_3; (*b*) the equivalent resistance; (*c*) the line current.

(*a*) In a parallel circuit, $E_1 = E_2 = E_3$, etc. Hence $E_3 =$ *40 volts*

$$R_3 = \frac{E_3}{I_3} = \frac{40}{0.40} = 100 \text{ ohms}$$

(*b*) $$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} = \frac{1}{200} + \frac{1}{600} + \frac{1}{100} = \frac{10}{600}$$

$$R_{eq} = \frac{600}{10} = 60 \text{ ohms}$$

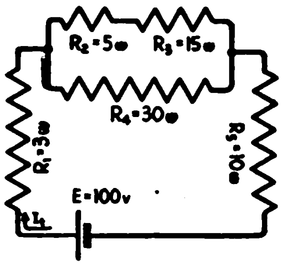
(c) $I_t = \frac{E_t}{R_{eq}} = \frac{40}{60} = 0.667$ **amp.**

Note: The student is advised to check this result by finding the three branch currents and adding them.

Series and Parallel Connections in the Same Circuit. A circuit may contain a group of resistances in parallel, with the entire combination in series with other resistances, some of which may themselves be in parallel with each other. Such circuits may appear to be quite complicated; actually the currents and voltages in such circuits can be found by applying the principles used in simpler circuits.

TYPICAL PROBLEM

Given five resistances connected as shown in the diagram. Find the current through each resistance and the voltage drop across each.



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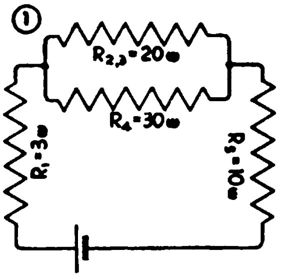

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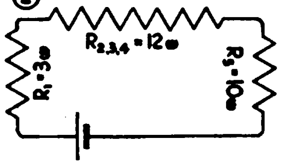

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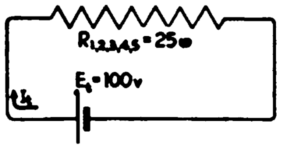

(a) The first thing to do is to find the equivalent resistance of the entire circuit by replacing the parallel combination by its equivalent resistance. To do this we proceed as follows:

(1) R_2 and R_3 are in series; therefore their equivalent resistance is simply their sum:

$$R_{2,3} = R_2 + R_3 = 5 + 15 = 20 \text{ ohms}$$

(2) $R_{2,3}$ is in parallel with R_4. Find the equivalent resistance of this combination as follows:

$$\frac{1}{R_{2,3,4}} = \frac{1}{R_{2,3}} + \frac{1}{R_4} = \frac{1}{20} + \frac{1}{30} = \frac{5}{60}$$

$$R_{2,3,4} = \frac{60}{5} = 12 \text{ ohms}$$

We have now changed the circuit into a simple series circuit whose resistance is easily found:

(3) $R_{1,2,3,4,5} = R_1 + R_{2,3,4} + R_5 = 3+12+10 = 25$ **ohms**

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(*b*) We now find the total current sent through this resistance by a voltage of 100 volts:

$$I_t = \frac{E_t}{R_t} = \frac{100}{25} = 4 \textbf{ amp}$$

This current of 4 amp is flowing through R_1 and R_5. However, we know that it divides in the parallel circuit. To find out how it divides, we must find the voltage drop across the parallel branch.

(*c*) $R_{2,3,4}$ represents this parallel branch in every way. Therefore the voltage drop across this equivalent resistance must be the voltage drop across the parallel branch. By Ohm's law,

$$E_{2,3,4} = IR_{2,3,4} = 4 \times 12 = 48 \textbf{ volts}$$

(*d*) Since we now know the voltage across the parallel circuit, we can analyze it just as we would analyze any simple parallel circuit.

(1) The voltage across R_4 is 48 volts (from step *c*). Therefore:

$$I_4 = \frac{E_4}{R_4} = \frac{48}{30} = 1.6 \textbf{ amp}$$

(2) The voltage across the series circuit, R_2 and R_3, is also 48 volts; this resistance, $R_{2,3}$, is 20 ohms. Therefore:

$$I_{2,3} = \frac{E_{2,3}}{R_{2,3}} = \frac{48}{20} = 2.4 \textbf{ amp} = I_2 = I_3$$

Check:

$$I_t = I_{2,3} + I_4$$
$$4 = 2.4 + 1.6$$

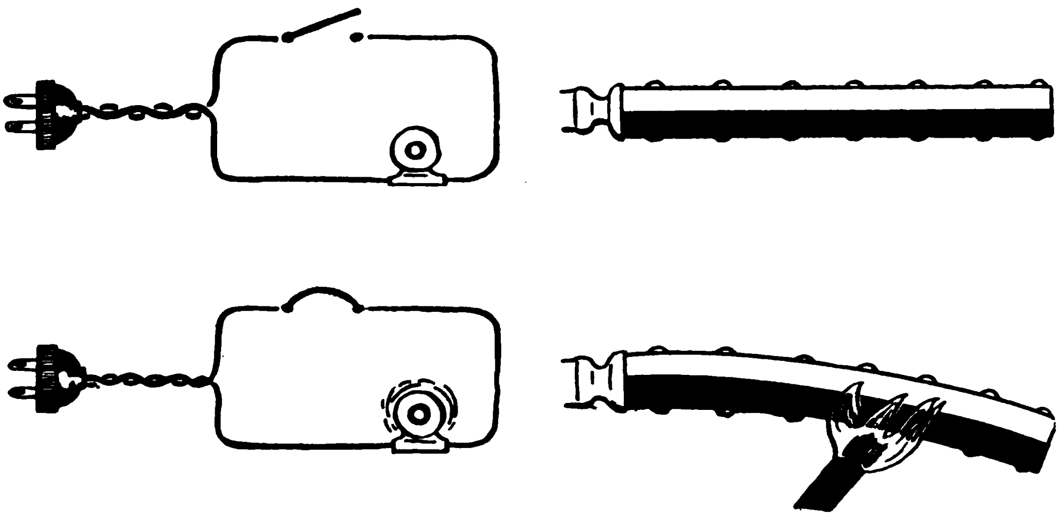
(*e*) Knowing all currents, we can now find all the voltage drops:

(1) $E_1 = I_1R_1 = 4 \times 3 = 12$ **volts**
(2) $E_2 = I_2R_2 = 2.4 \times 5 = 12$ **volts**
(3) $E_3 = I_3R_3 = 2.4 \times 15 = 36$ **volts**
(4) $E_4 = I_4R_4 = 1.6 \times 30 = 48$ **volts**
(5) $E_5 = I_5R_5 = 4 \times 10 = 40$ **volts**

Check:

$$E_2 + E_3 = E_4 \qquad E_1 + E_4 + E_5 = E_t$$
$$12 + 36 = 48 \qquad 12 + 48 + 40 = 100$$

The Thermostat. A thin strip of brass and a thin strip of steel firmly fastened together along their length constitute a *compound bar* or *bi-metallic strip*. When this compound bar is heated, one metal expands more than the other. The bar bends to permit one metal to become longer and still be attached to the other. The metal with the greater coefficient of expansion will be on the outside of such a bend. For a compound bar of brass and steel, the brass will be on the outside of the bend when the bar is heated. If the bar is cooled, as by surrounding it with dry ice, the bending will be in the opposite direction.



The Compound Bar. The diagram shows the use of a compound bar for controlling the motor of an electric refrigerator. The compound bar is inside the refrigerator. If the temperature rises too high, the bar bends, closes the motor circuit, and starts the refrigerator. When the temperature has been lowered to the proper temperature, the compound bar straightens out and disconnects the motor.

Compound bars are widely used in *thermostats* to open or close electric circuits and thus control heat and temperature automatically. The bending of the bar in one direction when a room, for example, becomes warmer, opens an electric circuit and thus turns off the stoker, oil burner, or blower. When the room cools to a predetermined temperature, the bar straightens out and again closes the circuit, thereby turning on the heat. Incubators, refrigerators, electric ovens, and numerous other devices are regulated as to temperature in this way.

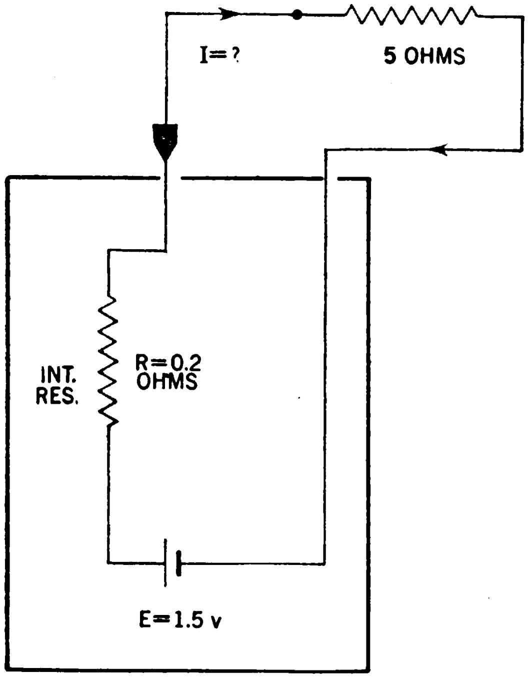
In automatic electric switches which turn lights off and on, or operate flashing signals intermittently, a small compound bar bends back and forth with temperature changes caused by a little heater coil wound around it.

Compound bars are also used to operate fire alarms or signals.

CELL CIRCUITS

Current Produced by Cells. As explained on page 32, the voltage generated by a given cell is not affected by the size of the plates, the distance between them, the amount of electrolyte, or any other factor except the nature of the materials used as electrodes. However, the amount of current which can safely be drawn from a cell does depend upon these factors. In general, the larger the plates of a cell, the greater the current which the cell can normally provide.

Internal Resistance of a Cell. Another factor which influences the amount of current delivered by a cell is its *internal resistance.* If the emf of a cell is measured with a high resistance voltmeter (so that very little current flows), the reading obtained is called the *open-circuit voltage* of the cell. It is the emf actually being developed by the chemical action within the cell. If this cell is now connected to a fairly low resistance, the current which flows will be *less* than what would be expected; and if the voltage across the cell terminals is now measured it will be found to be *less* than the open-circuit value. The reason for this is that the cell itself has an internal resistance, and the current flowing through this internal resistance produces a voltage drop



The part of the circuit enclosed in the black box is the equivalent circuit of the cell.

inside the cell. Consequently the terminal voltage of the cell is reduced.

In order to analyze any circuit containing a cell or other source of voltage, the internal resistance of the source must be considered. This is most easily done by replacing the actual cell by its *equivalent circuit.* This equivalent circuit consists of a source of voltage in series with a resistance equal to the internal resistance of the actual cell. The emf of the equivalent cell is the same as the emf or open-circuit voltage of the actual cell.

TYPICAL PROBLEM

A dry cell has an open-circuit emf of 1.5 volts and an internal resistance of 0.2 ohms. (*a*) What current will flow when a resistance of 5 ohms is connected to the terminals, and (*b*) what will be the terminal voltage?

(*a*) $E = 1.5$ volts; $R_{eq} = 0.2 + 5 = 5.2$ ohms; $I = ?$

$$I = \frac{E}{R} = \frac{1.5}{5.2} = \mathbf{0.288\ amperes}$$

(*b*) $E_{terminal} = \text{emf} - IR_{int} = 1.5 - (0.288 \times 0.2) = \mathbf{1.44\ volts}$

or

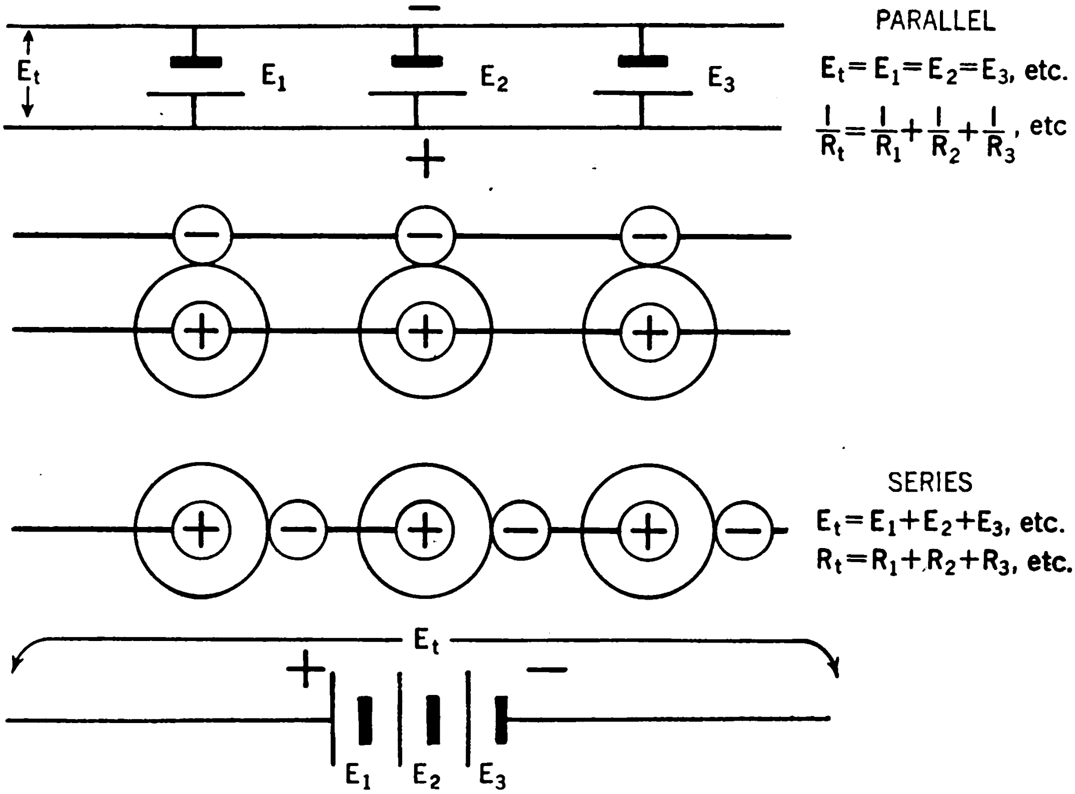
$$E = IR_{ext} = 0.288 \times 5 = \mathbf{1.44\ volts}$$

The internal resistance of a cell depends on the size of the plates and the distance between them. Increasing the plate area, or decreasing the distance between the plates, will decrease the internal resistance. The internal resistance of a cell increases as the cell is used; this resistance finally becomes so high that the cell is useless for its purpose and must be discarded. Note that the generated voltage remains the same throughout the life of the cell, but the terminal voltage (when the cell is in use) gradually diminishes as the internal resistance grows larger.

Cells in Series. When cells are connected so that the positive terminal of one is connected to the negative terminal of the next, etc., the cells are in series. The total emf of a number of cells in series is the sum of the emfs of all the cells; the internal resistance is likewise the sum of the separate resistances of each cell. Series connections of cells are used to obtain increased voltage—as in flashlights (where two or three 1.5-volt cells are connected in series with the bulb), in radio batteries of 4½ volts (3 cells),

$22\frac{1}{2}$ volts (15 cells), and 45 volts (30 cells), etc. The series connection does not make a greater current available. The maximum current which the combination can supply is still the maximum of any individual cell in the series.

Cells in Parallel. When more current is needed than a single cell can safely provide, several cells are connected in parallel—positive terminals connected together and negative terminals connected together. The total emf of the combination is the emf of a single cell, but the internal resistance is reduced in accordance with the formula for connecting resistances in parallel. Since the currents from each cell now add together, a greater total current is available.



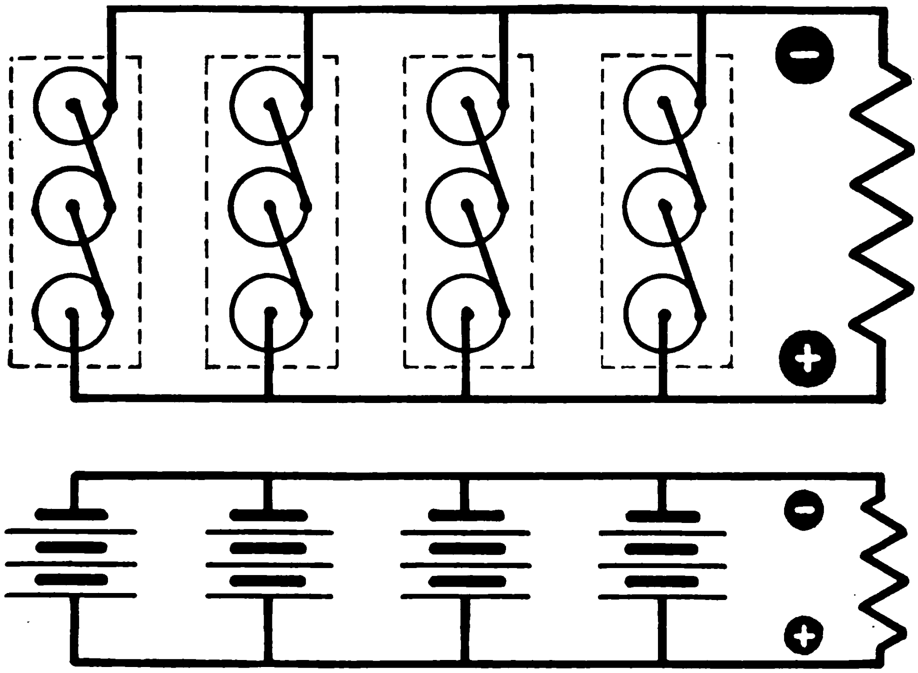
PARALLEL
$E_t = E_1 = E_2 = E_3$, etc.
$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$, etc
E_t
E_1
E_2
E_3
−
+
SERIES
$E_t = E_1 + E_2 + E_3$, etc.
$R_t = R_1 + R_2 + R_3$, etc.
E_t
+
−
E_1
E_2
E_3

Cells in Parallel and in Series

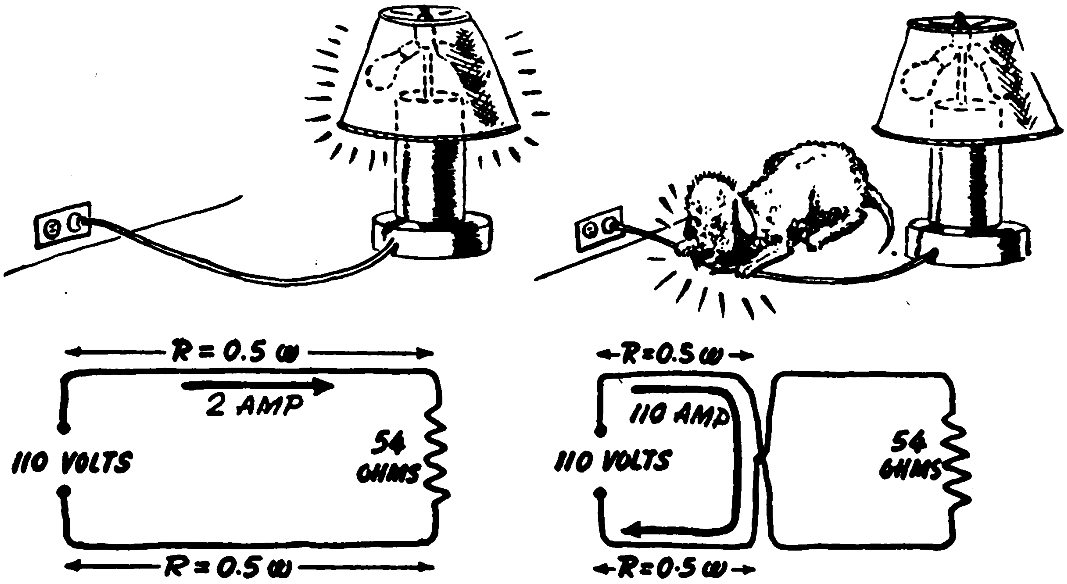
The ordinary No. 6 dry cell should not be permitted to supply a current in excess of $\frac{1}{4}$ ampere. When more current is needed, enough cells should be connected in parallel so that no single cell supplies more than this safe current value. When more than 2 or 3 amperes are required, storage batteries are usually employed.

As explained below in the discussion of short circuits, *cells connected in parallel must have the same emf.*

Series-Parallel Connections. If both voltage and current must be greater than can be obtained from a single cell, series-parallel connections may be employed. In such cases, groups of cells are connected in series, and the groups then connected in parallel as though each group were a single cell (see diagram). In making these connections, remember that *each group of cells in series must contain the same number of cells,* so that the emfs of the groups will be equal. Remember also that in a parallel connection, positive (+) terminals are joined, and negative (−) terminals are joined—never connect the + terminal of one group to the − terminal of another group.



"Short Circuit." Whenever anything is done to a circuit which so reduces its total resistance that an excessive current flows, the circuit is said to be *short-circuited.* Short circuits frequently occur in house circuits as a result of frayed lamp cords, in which the two wires leading to a lamp or other appliance touch each other instead of remaining insulated from each other. When this occurs, the circuit resistance may drop to less than 1 ohm, instead of a normal resistance of 50 ohms or more. An emf of 110 volts applied to a resistance of 1 ohm would produce a current of 110 amperes —high enough to melt the house wiring and possibly cause a fire in the walls of the building. (Fuses and circuit breakers—discussed later—are used to open a circuit when a short circuit occurs and thus prevent damage.)



A Short Circuit. The diagram at the left shows the circuit before the "short" occurs. The line resistance of 1 ohm represents all the wiring leading out to the main power supply in the street. At the right, a short circuit has occurred in the lamp cord. No current now flows through the lamp, but a heavy current of 110 amperes is flowing through the house wires.

When two cells of different emfs are connected in parallel, a short circuit results. A 4.5-volt cell in parallel with a 1.5-volt cell actually forms a closed series circuit with a net emf of 3 volts and a total resistance of perhaps 0.1 ohm (the combined internal resistance of the two cells). Three volts applied to a resistance of 0.1 ohm results in a current of 30 amperes, which soon damages the two cells. The current which flows circulates in a small loop consisting only of the two cells. Such wasteful circulating currents will flow even when there is just a small difference in emf between the cells in parallel. That is why cells connected in parallel should be identical in every way.

BEST ANSWER TEST

1. The voltage of 5 dry cells in series is (*a*) 5 times the voltage of 1 cell; (*b*) ⅕ the voltage of 1 cell; (*c*) the same as the voltage of 1 cell; (*d*) dependent on the resistance of the circuit.

2. In a series circuit, the quantity that is the same throughout is (*a*) resistance; (*b*) current; (*c*) voltage; (*d*) conductance.

3. Doubling the length of a copper wire (*a*) doubles its resistance; (*b*) halves its resistance; (*c*) quadruples its resistance; (*d*) doubles its conductance.

4. The resistance of a given length of iron wire is (*a*) directly proportional to its diameter; (*b*) inversely proportional to its diameter; (*c*) inversely proportional to the square of its diameter; (*d*) the same as for any other kind of wire of the same length and size.

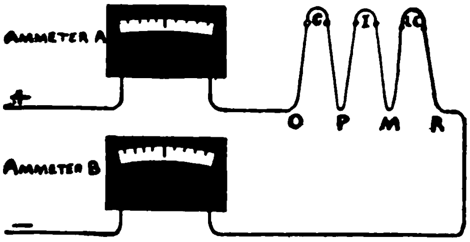
5. Increasing the temperature of the nichrome wire in an electric toaster (*a*) decreases; (*b*) increases; (*c*) has no effect, on its resistance.

QUESTIONS

1. What is the effect of each of the following on (1) the voltage, (2) the internal resistance of a voltaic cell? (*a*) Materials of which the cell is constructed; (*b*) size of the plates; (*c*) distance between the plates; (*d*) area of plates in contact with the electrolyte.

2. Which has the greater resistance to the flow of current: (*a*) A 2-meter length or a 4-meter length of copper wire, both of the same diameter? (*b*) Two tungsten filaments connected in series or the same two filaments connected in parallel? (*c*) A 2-meter length of copper wire 1/10 in in diameter or the same length of copper wire 1/5 in in diameter? (*d*) A 2-meter length of copper wire or a 2-meter length of iron wire, both of the same diameter? State the principle involved in each case.

3. A copper wire and an iron wire are connected in parallel with the binding posts of a battery. The iron wire has five times the resistance of the copper wire. (*a*) How many amperes are flowing in the copper wire when 1 ampere is flowing in the iron wire? (*b*) State the law you would apply to compute the equivalent resistance.



4. The diagram shows three equal lengths of wire through which a steady current is flowing. *C* is copper; *I* is iron of the same size as the copper; *LC* is copper of much larger diameter than *C*.

Select in *each* case from the expressions in parentheses the one that makes the statement correct.

(*a*) If ammeter *A* reads 6 amperes, ammeter *B* will read (6, more than 6, less than 6) amperes.

(*b*) A voltmeter connected from *O* to *P* will read (the same as, more than, less than) one connected from *M* to *R*.

(*c*) A voltmeter connected from *O* to *P* will read (the same as, more than, less than) one connected from *P* to *M*.

(*d*) The current in wire *C* is (the same as, greater than, less than) the current in *I*.

5. Explain the reasons for using parallel wiring instead of series wiring in homes and offices.

PROBLEMS

1. Calculate the resistance of 200 ft of copper wire, the diameter of which is 32 mils. ($k = 10.4$) Ans. 2.03 ohms

2. How many feet of the wire in problem 1 must be used in winding a coil of 5 ohms? Ans. 492 ft

3. How much current will be sent through (*a*) 20 ohms, (*b*) 100 ohms, (*c*) 2000 ohms by a potential difference of 10 volts?
Ans. (a) 0.5 amp (b) 0.1 amp (c) 0.005 amp

4. What difference of potential is required to send (*a*) 10 amperes through a 5-ohm resistance; (*b*) 0.5 ampere through a 500-ohm resistance; (*c*) 2 "mils" (milliamperes) through a 1-megohm resistance?
Ans. (a) 50 v (b) 250 v (c) 2000 v

5. What resistance, when connected to a 550-volt line, will permit a current flow of (*a*) 50 amperes; (*b*) 2 amperes; (*c*) 11 mils?
Ans. (a) 11 ohms (b) 275 ohms (c) 50,000 ohms

6. What is the resistance of 40 ohms, 60 ohms and 80 ohms connected (*a*) in series, (*b*) in parallel? Ans. (a) 180 ohms (b) 18.5 ohms

7. (*a*) How much line current will flow when five 100-ohm lamps are connected in parallel across a 110-volt line? (*b*) How much current does each lamp draw? (*c*) What voltage would be needed to send 1 ampere through these five lamps connected in series?
Ans. (a) 5.5 amp (b) 1.1 amp (c) 500 v

8. What is the resistance of an electric heater drawing 4 amperes on a 110-volt circuit? Ans. 27.5 ohms

9. (*a*) What resistance should be put in series with a 110-volt lamp that draws 2 amperes, in order to light it from a 200-volt circuit? (*b*) What would be the voltage drop across this resistance?
Ans. (a) 45 ohms (b) 90 v

10. The voltage at a power house supplying 50 amperes to a trolley car one mile away is 550 volts. (*a*) What is the voltage drop through the connecting wires whose resistance is 0.5 ohm? (*b*) What is the voltage at the trolley? Ans. (a) 25 v (b) 525 v

11. (*a*) What is the terminal voltage of a 6-volt storage battery, whose internal resistance is 0.05 ohm when it is being charged at the rate of 8 amperes? (*b*) When it is discharging at the rate of 10 amperes?
Ans. (a) 6.4 v (b) 5.5 v

12. Resistors of 800 ohms and 200 ohms are connected in parallel, and the combination is then connected in series with a resistor of unknown value. When the voltage across the entire circuit is 160 volts, the current through the 200-ohm resistor is 0.16 amp. Calculate: (*a*) the voltage across the parallel branch; (*b*) the current through the 800-ohm resistor; (*c*) the voltage across the unknown resistor; (*d*) the resistance of the unknown resistor. Ans. (a) 32 v (b) 0.04 amp (c) 128 v (d) 640 ohms

13. How much current would 20 cells in series, each having an emf of 2 volts and an internal resistance of 0.1 ohm send through three resistances of 20, 30, and 60 ohms, respectively, connected in parallel?
Ans. 3.33 amp

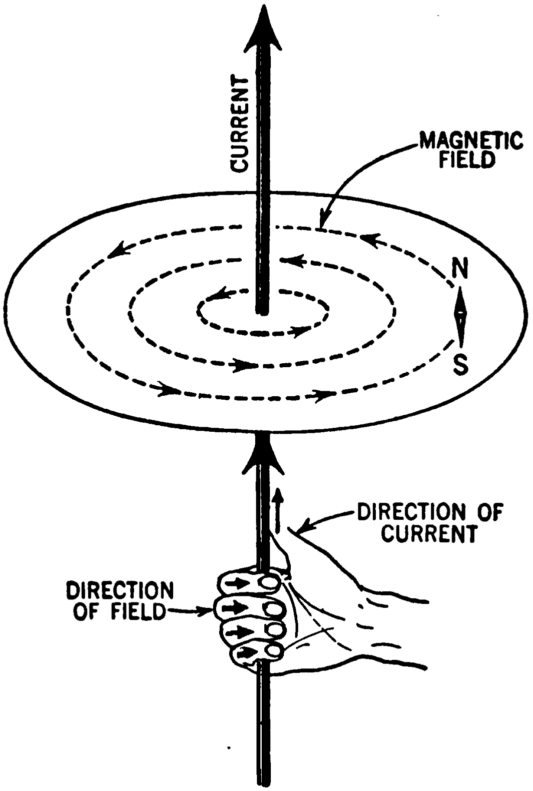
FIVE— ELECTROMAGNETISM

ELECTRICITY IN MOTION PRODUCES MAGNETISM

Oersted's Discovery. A Danish physicist, Oersted, in the year 1819, discovered the presence of a magnetic field around a current-carrying wire. This field around a straight wire carrying a current consists of concentric circles in planes perpendicular to the wire. The presence and pattern of the field can be seen by passing current through a vertical wire which runs through a piece of cardboard supported horizontally. When iron filings are sprinkled on the cardboard and it is tapped lightly, the filings align themselves in circles around the wire, thus revealing the magnetic lines of force.

The direction of these circular lines of force can be determined by placing a small compass on the cardboard. The north pole of the compass points in the direction of the magnetic field (magnetic lines of force run from *N* through the air to *S*). If a straight, current-carrying wire is held *above* a compass in such a manner that the current flows from north to south, the north pole of the compass needle is deflected to the east. The needle points in the direction of the field. If the direction of the current is reversed, the needle is deflected to the west.

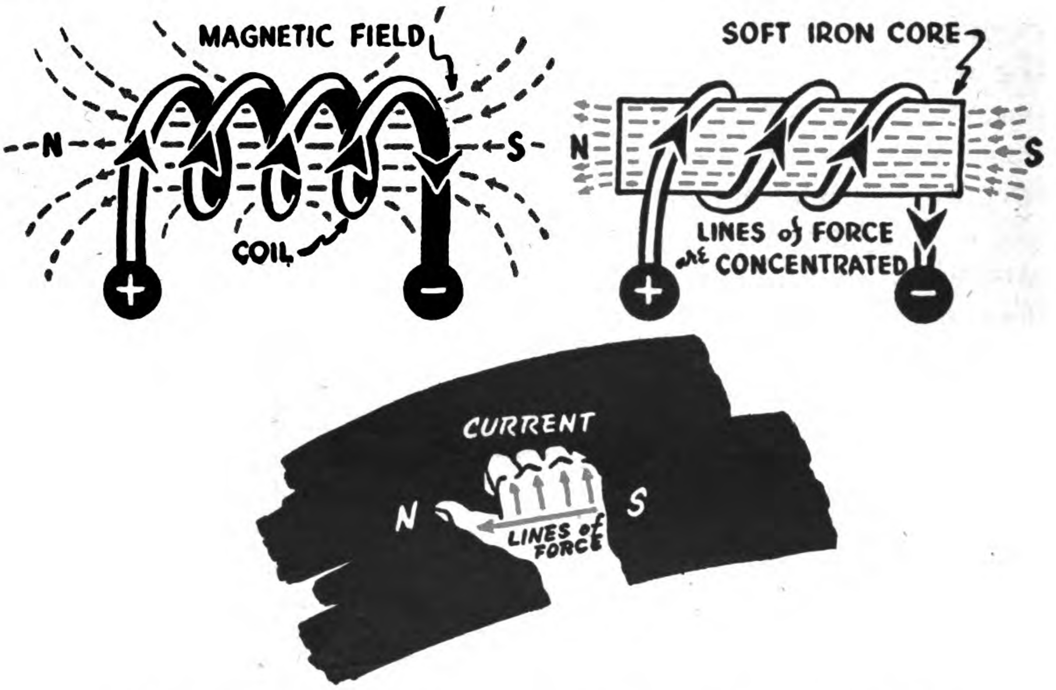
The *right-hand thumb rule* is useful in determining the di-



A current produces a magnetic field; the right-hand thumb rule shows the direction of the current and the field.

rection of the magnetic field about a current-carrying wire. *Grasp the wire with the right hand so that the thumb points in the direction of current flow (+ to −); then the fingers will curl around the wire in the direction of the magnetic field.*

Magnetic Field About a Current-Carrying Coil. A more intense magnetic field can be obtained from a small current flowing in a wire by looping the wire to form a coil. It is found that the coil closely resembles a bar magnet, both in its magnetic action on a compass needle and in the pattern of its magnetic field.

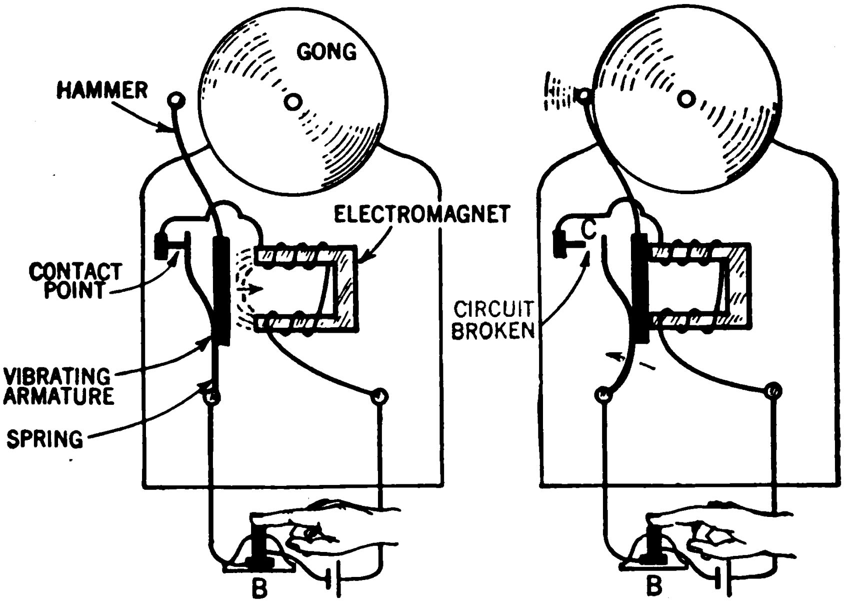


The Electromagnet. Magnetic lines of force are in red.

If the coil is wrapped around a bar of iron or steel, the magnetic field becomes still stronger. This is because iron and steel offer less resistance than air to the magnetic lines of force, and also because the bar becomes magnetized and its lines of force add to those of the coil. A current-carrying coil of wire with an iron core is an electromagnet.

The right-hand thumb rule also enables us to determine which end of an electromagnet is a north pole and which is a south pole: *Grasp the coil of the electromagnet with the right hand so that the fingers curl in the direction of current flow; then the* *thumb will point to the north pole of the electromagnet.* The polarity of an electromagnet thus depends upon the direction of the flow of current.

Characteristics of Electromagnets. The strength of an electromagnet depends upon (1) the number of amperes flowing in the coil; (2) the number of turns in the coil; (3) the permeability of the core. With a given material used as the core (usually soft iron), the strength of an electromagnet depends upon the number of *ampere-turns;* that is, the product of the current in amperes and the number of turns in the coil. An electromagnet having 1000 turns of wire carrying 4 amperes is equal to one having 2000 turns of wire carrying 2 amperes; both have 4000 ampere-turns.



The Electric Bell

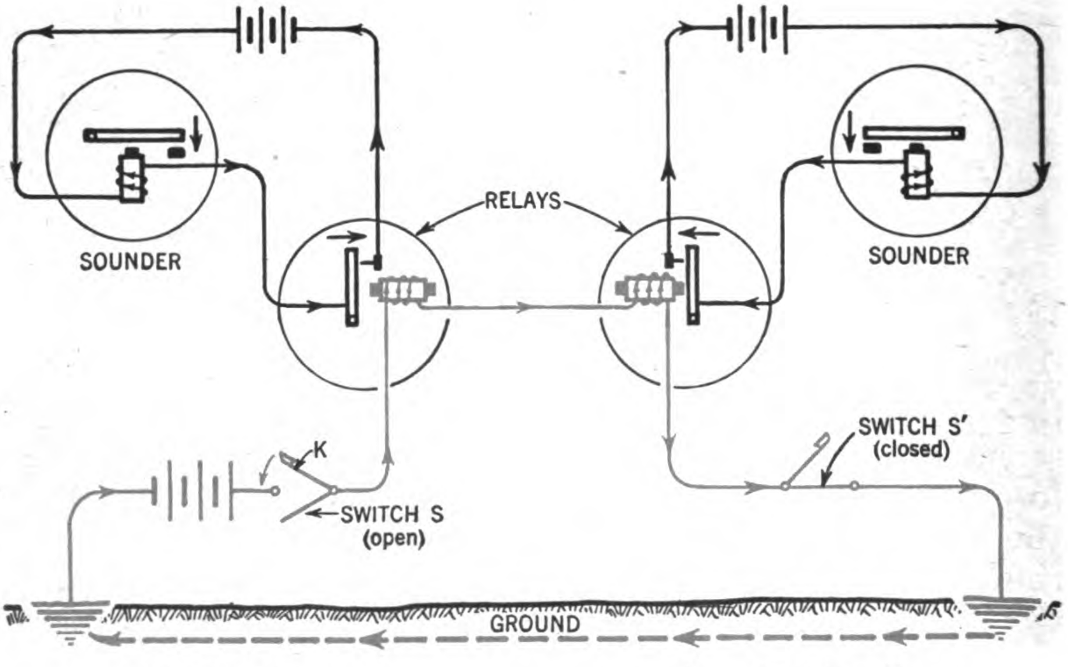
The principal advantages of electromagnets are: (1) they can be made much stronger than permanent magnets; (2) their field strength is easily controlled by regulating the current; (3) they lose practically all their magnetism almost immediately when the current is turned off, provided that the core is soft iron (low retentivity). If the core were hard steel (high retentivity), it would retain much of its magnetism and become a permanent magnet.

Applications of the electromagnet are found in the electric bell, the magnetic hoist, the relay, the telephone and telegraph;

in electric motors, generators, and transformers; and in electrical measuring instruments, such as galvanometers, ammeters, voltmeters, and others. In fact, an electromagnet is a part of nearly every electrical machine. The magnetic field is the most widely applied of the effects which current flow produces.

The Electric Bell. The essential parts of the electric bell are shown in the diagram on page 65. When the circuit is completed, by closing the push button *B*, the current flows through the electromagnet. The soft iron vibrating armature is attracted by the electromagnet and as it moves over, the circuit is broken at *C*. (See right side of diagram.) When the current stops, the electromagnet loses its magnetism and hence its attraction for the armature. A spring moves the armature back and it again makes contact at *C*, thus completing the circuit and re-energizing the electromagnet. In this way, the armature moves back and forth and the hammer attached to it keeps striking the gong—as long as the push button is closed.

The Relay and the Telegraph Circuit. The diagram shows the set-up of a simple telegraph circuit. When station *A* is sending, switch *S* is open but *S′* is closed; thus the circuit is controlled by



Station A **Station B**

The relay circuit is shown in red.

means of the sender key *K*. When this key is closed, the circuit is complete (the earth serves as one conductor between the two stations), and current flows through the coils of the relay at station *B*. The relay is really a sensitive electromagnetic switch having a coil of many turns of fine wire and a light-weight armature. When the feeble main line current flows through the coils of the relay, electromagnetism is produced which pulls the armature against a contact point. This closes the local circuit and allows a heavier current to flow through the coils of the sounder. Electromagnetism pulls the armature of the sounder downward against a setscrew.

When the key is released at *A*, the circuit is broken; the relay electromagnet is de-energized, the local circuit is opened, and the armature of the sounder is released. The sounder thus makes two clicks, one when it is pulled down and another when it is released. The time interval between these two clicks is interpreted as a dot or a dash by the operator, a short time interval representing a dot and a longer one a dash. Dots and dashes are translated into messages according to the Morse code.

Other Uses of Relays. Relays have many applications in electrical devices. In all cases, however, they have one general purpose—to control a circuit carrying a large current by means of a low-current circuit. For example, relays are usually used in photoelectric cell circuits (see page 170). The weak current produced by the photoelectric cell cannot directly operate devices such as motors, bells, or signal lights; the small current can, however, operate a relay; the relay then acts as a switch to turn on or off the main power circuit which does operate these heavier devices.

The Circuit Breaker. The circuit breaker is simply a switch operated by an electromagnet. The coil of the electromagnet is inserted in series with the main line of a circuit in which excessive currents must be avoided. The switch itself is attached to a soft iron plunger held in place by a spring catch. As long as the main line current remains below a predetermined size, the electromagnet coil is not strong enough to pull the plunger away from the catch. If, however, the current rises above a safe value, the electromagnet becomes strong enough to operate the switch, thus instantly opening the circuit. The purpose of the circuit breaker is the same as that of a fuse. However, a circuit breaker need not

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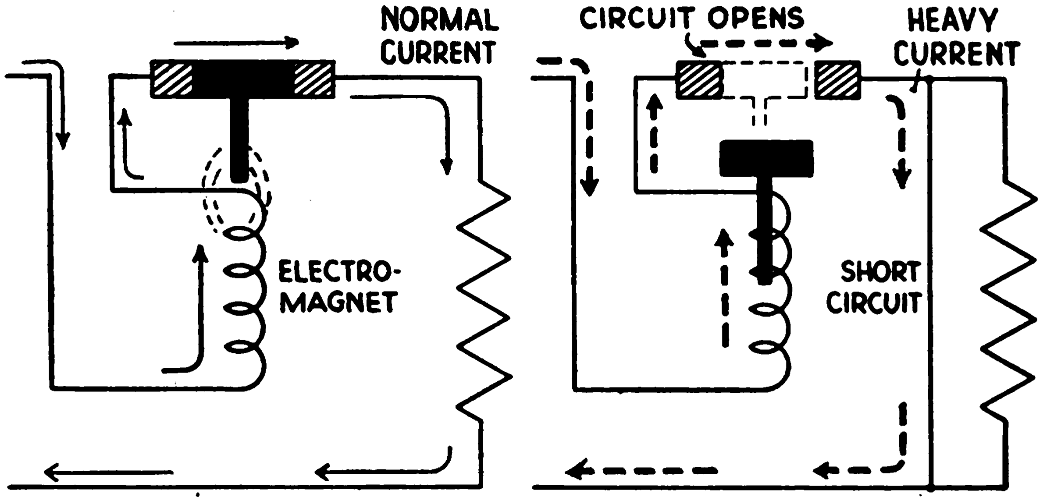


The electromagnet is not strong enough to pull the plunger down when normal current is flowing. When a short circuit occurs, the heavy current strengthens the magnet, and the circuit is opened. Current immediately stops flowing.

be replaced after operating—simply reset. The circuit breaker is also more practical for large power circuits in which the normal current is several hundred amperes.

ELECTRIC METERS

Many electric meters are of the indicating type; that is, the desired reading is obtained from the movement of a pointer across a calibrated scale. The device in this type of meter that causes the pointer to move is called the *meter movement*. Many meter movements depend for their operation upon magnetic attraction and repulsion.

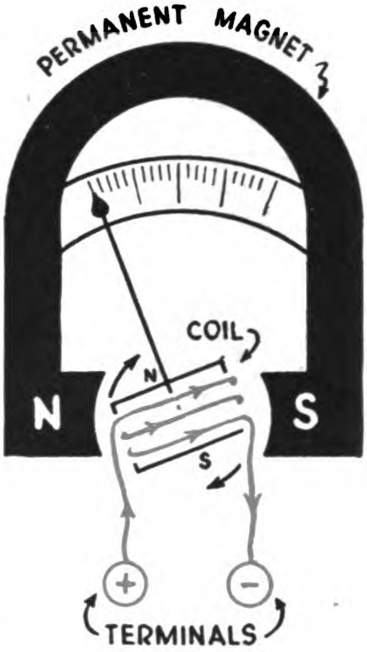
The Weston Meter Movement. The meter movement used most extensively for measuring DC, and also with certain modifications for AC, is called the *Weston* movement, after its inventor. This type of movement is also known as the permanent-magnet moving-coil type.

The Weston movement consists essentially of a small rectangular coil of fine wire, suspended on jewel bearings between the poles of a permanent magnet, and free to rotate against the retarding force of two spiral springs. The springs also serve to carry current into and away from the coil. A non-movable soft iron core within the coil strengthens the magnetic field through it.

When current flows through this coil, the magnetic field produced about the coil reacts with the magnetic field of the permanent magnet causing the coil to rotate and move the attached pointer across a scale. The amount of rotation of the coil depends upon the strength of the magnetic field produced by the coil, and hence depends upon the size of the current flowing in the coil. Modern Weston movements are carefully constructed so that the deflection of the pointer is directly proportional to the current in the coil.

The Galvanometer. A galvanometer is a device for detecting very small electric currents, and their direction, but not for measuring their value in practical units. Portable galvanometers commonly operate on the Weston principle. Their coils will be burned out by currents of more than a few microamperes.

The Ammeter. To extend the range of a galvanometer, that is, to enable it to read larger currents, it is only necessary to add a *shunt*. The galvanometer then becomes an *ammeter*. A shunt is a strip of metal of low resistance connected across the terminals of the coil of the meter, that is, in parallel with the coil. The shunt carries the major portion of the current entering the meter, while a small, fixed percentage of the total current flows through the coil. Thus if 10 amperes flow through an ammeter, 9.95 amperes may go through the shunt and only 0.05 amperes through the coil itself. Ammeters usually have two or three shunts from which one is selected to adapt the meter to the desired range; the larger the current to be measured, the smaller the resistance of the shunt must be. An ammeter is connected in series with the circuit in which the current is to be measured; that is, the circuit is opened at some convenient point and the ammeter is inserted.



The Weston Meter. As current flows through the coil (shown in red) a magnetic field is set up with the polarity as indicated. The N-pole of the coil is repelled by the like pole of the permanent magnet, causing the coil to rotate.

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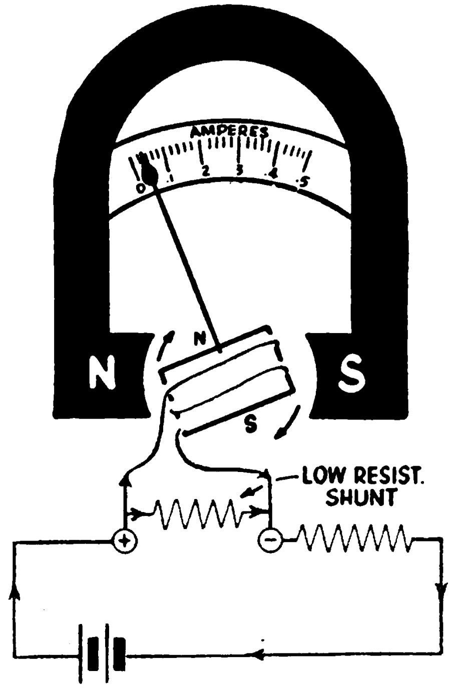
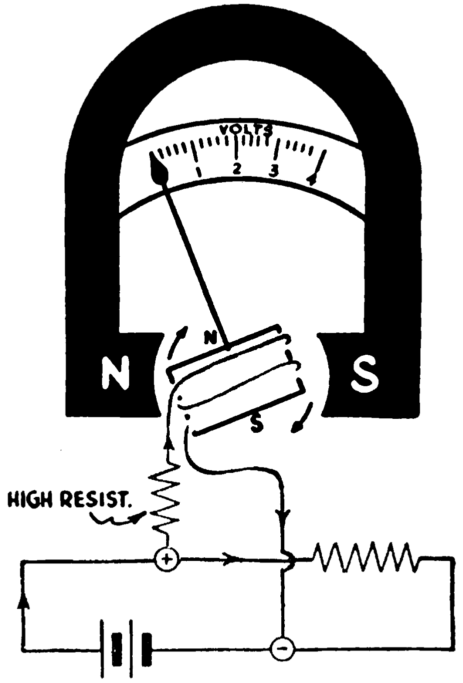


Ammeter



Voltmeter

The Voltmeter. A voltmeter is essentially a galvanometer with a high resistance (several thousand ohms) in series with the coil, so that it can safely be connected across a line, or other relatively large voltage. Such a high resistance connected in series protects the delicate coil, since only a very small current can flow through the meter. For example, if the voltmeter resistance is 10,000 ohms and the voltmeter is put across a 100-volt line, the current through the voltmeter will be only 0.01 ampere, as can be seen from Ohm's law:

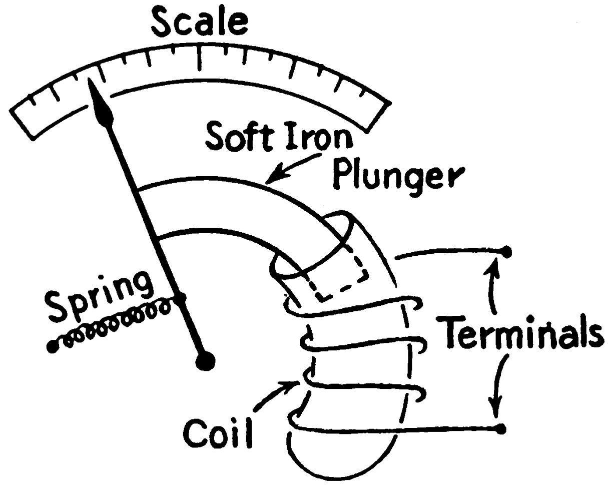
$$I = \frac{E}{R};\ I = \frac{100}{10{,}000} = 0.01 \text{ ampere}$$

Although the voltmeter movement actually measures the current flowing through it, the scale is calibrated to read voltage directly. For example, a voltmeter ($R = 10{,}000$ ohms) is connected across two points between which the difference in potential is to be measured, and a current of 0.02 ampere flows. The voltage, therefore, must be 200 volts:

$$E = IR;\ E = .02 \times 10000 = 200 \text{ volts}$$

Therefore, instead of being marked .02 amperes, the scale is marked 200 volts. Voltmeters frequently have two or more high resistance coils from which to select for adapting the meter to the desired range; the larger the potential difference to be measured, the larger the resistance of the coil must be.

The Plunger Vane Movement. Although the Weston movement is extremely accurate, it is a delicate mechanism because of the moving coil, and relatively bulky and heavy because of the permanent magnet. The plunger vane movement, illustrated in the diagram, is simpler, more compact, and more rugged. The current to be measured flows through a stationary coil. The only moving part is a soft iron vane which is "sucked" into the coil by the magnetic field produced when current flows through the coil. The iron vane is held back by a spring, so that the motion of the vane is proportional to the strength of the attracting magnetic field; hence it is also proportional to the current in the coil. A pointer is attached to the vane.



This type of movement can be used in ammeters and voltmeters, using shunts and resistances as in the case of the Weston meters. It is also satisfactory for alternating current measurements because the magnetic attraction of the iron vane does not depend on polarity of the coil.

Circuit Use of Meters. In order to measure the current flowing in a circuit, that current must pass through the meter. In other words, ammeters must be connected in series with the circuit whose current is to be measured. One of the important requirements of a good meter is that it leave undisturbed the conditions in the circuit when it is inserted. In the case of an ammeter, this means that the meter must have a low resistance, so that when it is added to the circuit the total resistance of the circuit will not be changed to any important extent. This principle applies to all series instruments, such as relays, circuit breakers, and fuses.

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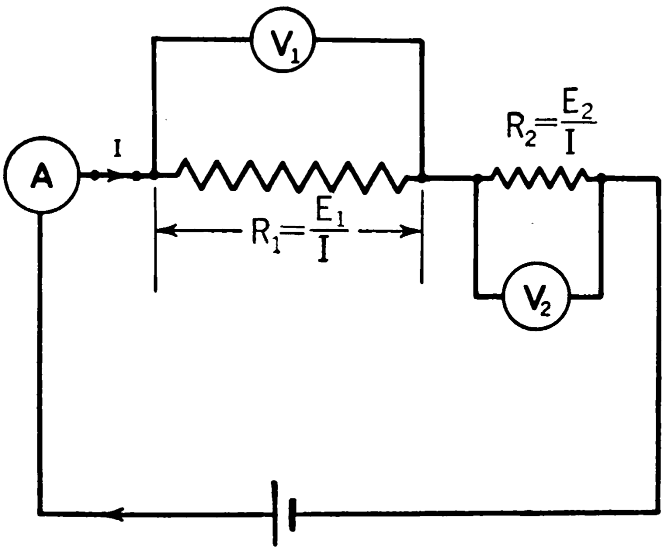


The Voltmeter-Ammeter Method of Determining Resistance. The resistance of any part of a circuit is equal to the voltage drop across that part divided by the current flowing through it. In the diagram, R_1 is found by dividing its voltage drop (reading of voltmeter V_1) by the current (reading of ammeter A). The value of R_2 is similarly found by using the reading of V_2.

Voltmeters must satisfy the opposite requirement — very high resistance—because they must be connected in parallel with the portion of the circuit whose voltage drop is to be measured. If the voltmeter resistance is too low, it will lower the total resistance of the circuit, and change the distribution of voltage. The voltage across a given resistor with the meter connected may be quite different from the voltage when the meter is removed, if the meter has too low a resistance.

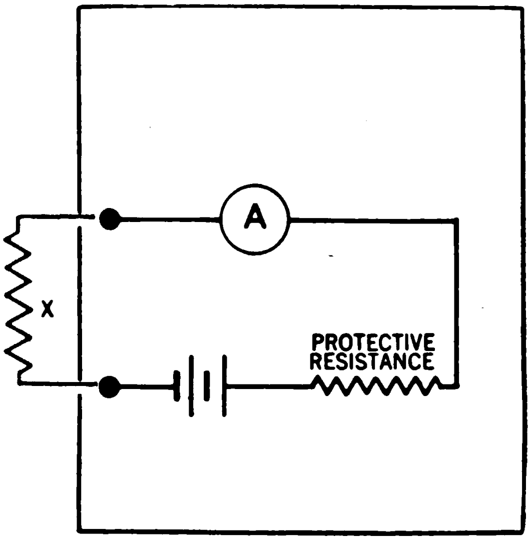
Measuring Resistance by Means of Ammeter and Voltmeter. By means of voltmeter and ammeter readings, the value of an unknown resistance may be calculated, using Ohm's law. The conductor whose resistance is to be determined is connected in an electric circuit, so that a current will flow through it. The amount of current flowing is measured by an ammeter inserted in the circuit; at the same time, a voltmeter is connected to the ends of the unknown resistance and the voltage drop across the resistance is thereby measured. Applying Ohm's law:

$$R = \frac{E}{I} = \frac{\text{reading of voltmeter}}{\text{reading of ammeter}}$$

This is called the voltmeter-ammeter method of determining resistance.

Note that the ammeter is reading the current through the resistance *plus* whatever small current is flowing through the voltmeter. In most cases, this voltmeter current is so small (compared with the main current) that it may be neglected. Where extreme accuracy is required, however, the voltmeter current must be subtracted from the ammeter reading (to find the true resistor current) before the calculation of resistance is made. The voltmeter current is readily calculated by dividing its voltage reading by its resistance (usually marked on the meter dial or on an attached label).

The Ohmmeter. Resistance may also be measured by an instrument called an *ohmmeter*, which operates on the ammeter-voltmeter method of measuring resistance. It contains a dry cell of fixed voltage, and an ammeter, connected as shown in the diagram. When the terminals of the ohmmeter are connected to the terminals of an unknown resistance (x), the circuit is completed and the ammeter reads the current which flows. Since the current depends on the resistance, the scale can be calibrated to read ohms directly—the voltage being fixed by the self-contained battery.



The Ohmmeter Method of Determining Resistance. The ohmmeter is shown in black; the resistance being measured, in red.

As the resistance, x, is made smaller, the deflection of the ammeter becomes greater; as the resistance is increased, the meter deflection is reduced. In other words, low resistance readings correspond to high currents through the meter. Zero current means infinite resistance (open circuit); maximum deflection means zero resistance (test prods touched together). An inspection of the ohmmeter scale will show that the high resistance readings occur where the low current readings would normally be.

When the test prods are touched together, the current is limited only by the protective resistance in the meter itself. In this condition, the meter should read zero resistance. If it does not, the

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adjusting knob should be turned until it does. This knob merely changes the value of the protective resistance, which is a simple rheostat. Unless this preliminary adjustment is made before each use of the ohmmeter, its readings are likely to be incorrect.

BEST ANSWER TEST

1. The shape of the lines of force around a current-bearing conductor is (*a*) oval, (*b*) horseshoe, (*c*) circular, (*d*) parabolic.

2. The man who first observed the magnetic effect of a current was (*a*) Edison, (*b*) Faraday, (*c*) Oersted, (*d*) Henry.

3. Increasing the current in an electromagnet makes it (*a*) have more magnetism, (*b*) have less magnetism, (*c*) have neither more nor less magnetism, (*d*) have more resistance.

4. The current flows north in a wire. The needle of a magnet placed *above* the wire will (*a*) point north, (*b*) point south, (*c*) point east, (*d*) point west, (*e*) spin very rapidly.

5. A coil of insulated wire is wound as follows: the wire is first bent double, forming a long narrow hairpin; this double wire is then wound around a cardboard cylinder. When a current is sent through the two free ends, (*a*) a short circuit will result; (*b*) the magnetic field produced will be twice as strong as a single wire coil; (*c*) the magnetic field will have two like poles at its ends; (*d*) there will be little or no magnetic field produced.

6. The purpose of a relay in a telegraph circuit is to (*a*) produce a loud click; (*b*) introduce delayed action response; (*c*) control a strong local circuit; (*d*) provide secrecy of messages.

7. An electromagnet can be used to operate a circuit breaker because (*a*) the strength of its magnetic field is proportional to the amount of current through it; (*b*) it has a high resistance which prevents short circuits; (*c*) it will not attract copper bus bars; (*d*) it has no moving parts.

8. If the shunt of an ammeter is accidentally disconnected from a circuit, (*a*) the circuit will be opened; (*b*) the pointer will return to zero; (*c*) there will be no change in the reading; (*d*) the current will probably burn out the coil of the meter.

QUESTIONS

1. Describe the procedure for determining the electric resistance of a toaster, making use of an ammeter and a voltmeter.

2. (*a*) Explain how an electric current may cause the coil of a galvanometer to move. (*b*) What force brings the indicator back to zero when the circuit is broken? (*c*) How may a galvanometer be converted to a voltmeter?

3. What determines the strength of an electromagnet?

4. How do the relay and the sounder of a telegraph system differ?

5. In what direction will a freely-swinging electromagnet set itself? Explain.

SIX— WORK, ENERGY, AND POWER IN ELECTRIC CIRCUITS

WORK

Force. We all have a clear impression, in our minds, of what a force is like. We experience forces as "pushes" and "pulls." Nevertheless, we cannot say exactly what a force is, but only what it can do. A force is something which can do either of the following two things: (1) change (or tend to change) the motion of a body (as in the acceleration of a bullet by expanding gases in a gun barrel), or (2) change the shape of a body (as in the flattening of a bullet against a steel wall).

A common example of a force is the force of attraction between bodies—the force of gravitation. It is the gravitational attraction between the earth and all other bodies near the earth which accounts for the weight of those bodies. The weight of a body can be measured with a spring balance, in which the stretch of the spring is proportional to the weight of the body. By common agreement among scientists, a certain weight has been taken as a standard, and called *one pound.* All other weights are determined by comparison with this standard pound. Thus an object with a weight of 12 pounds is pulled by the earth with a force 12 times as great as the force on the standard one-pound weight, and will stretch a spring balance 12 times as much. The *kilogram* (equal to 2.2 pounds) is another standard unit of weight frequently used.

Other important natural forces, which have already been studied in previous chapters, are magnetism and the forces between charged bodies.

Work. A force may be present without producing motion; a book resting on a table is pulled downward by gravity, but the table exerts an equal upward force which prevents motion from actually occurring. On the other hand, you can exert a force with your hand which will lift the book against the downward force of gravity. In this second case, motion does occur, and the force which you exert moves upward with the book.

Whenever a force is exerted on a body, and the body moves in the direction of the force, ***work*** *is done.* In all cases where work is done, the force overcomes a resistance to produce motion. In lifting the book, the resistance overcome was the weight of the book. If the book had been pushed along the table, instead of being lifted, the resistance of friction would have been overcome. If the book had been thrown through the air, your hand would have overcome the resistance of inertia of the body (inertia is the resistance which every body offers to any change in motion of the body).

Work is done only while the force is moving and overcoming the resistance. If you stop lifting the book and merely hold it still in the air, you will still be exerting a force, but performing no work, because there is no motion. When you throw the book, you stop doing work as soon as the book leaves your hand, because you are no longer exerting a force on the book.

The amount of work done is measured simply by multiplying the force exerted by the distance through which it moves. If the force is measured in pounds (lb), and the distance in feet (ft), the work done is measured in *foot-pounds* (ft-lb). The foot-pound is the most common unit of work used in engineering calculations, although the kilogram-meter and the gram-centimeter are used in scientific investigations.

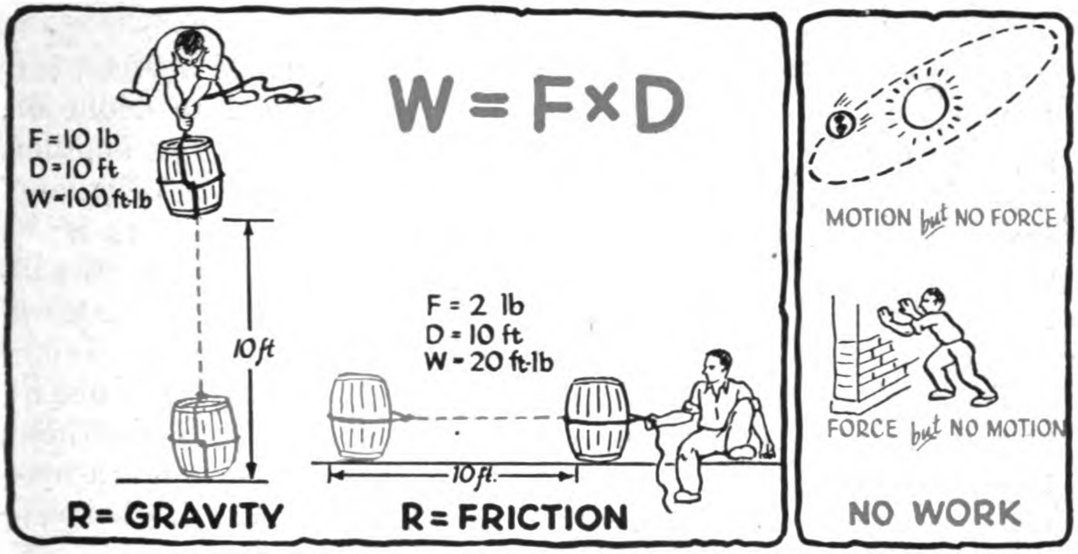
TYPICAL PROBLEM

How much work is done when you apply a force of ten pounds to pull a cart three feet?

Multiply the force (10 lb) by the distance through which the force acts (3 ft).

$$\begin{aligned}\text{work} &= \text{force} \times \text{distance}\\ &= F \times D\\ &= 10\text{ lb} \times 3\text{ ft} = \mathbf{30\ ft\text{-}lb}\end{aligned}$$

Work is done only when the force acts *in the direction of motion.* If a body moves at right angles to a force acting on it, no work is done by that force. Thus the force of gravitation holds the earth in its orbit around the sun, but this force is at right angles to the earth's motion—hence no work is done.



The Principle of Work

TYPICAL PROBLEMS

To be loaded into a gun, a shell weighing 60 lb was lifted 4 ft from the ground. How much work was done?

It takes a force of 60 lb to lift the shell vertically. Multiply this force by the distance through which the force acts:

$$\begin{aligned} W &= F \times D \\ &= 60 \text{ lb} \times 4 \text{ ft} = \mathbf{240 \text{ ft-lb}} \end{aligned}$$

A force of 50 lb, exerted parallel to the slope of a hill, pushed a loaded cart weighing 300 lb a distance of 10 ft along the hill. How much work was done?

$$\begin{aligned} W &= F \times D \\ &= 50 \text{ lb} \times 10 \text{ ft} = \mathbf{500 \text{ ft-lb}} \end{aligned}$$

Note: It is the force in the direction of motion (50 lb), not the weight, that determines the work done.

A student weighing 120 lb climbed a vertical distance of 42 ft in 15 sec. How much work did he do?

In calculating the work done, pay no attention to the time.

$$\begin{aligned} W &= F \times D \\ &= 120 \text{ lb} \times 42 \text{ ft} = \mathbf{5040 \text{ ft-lb}} \end{aligned}$$

ENERGY

Energy. In the study of mechanical and electrical devices, the term *energy* is frequently used. It is a hard word to define or explain, but for the present simply think of energy as another name for work. Or to be more exact, think of work as being one *kind* of energy. The particular kind of energy which work is, is called *mechanical energy* (because it is the kind which occurs in machines). Mechanical energy is, then, a force acting through a distance.

There are many other forms or kinds of energy. Heat is one of these forms; so is light; and so is the motion of bodies. From these few examples, you can see immediately that energy is not a material substance—but it is something which material bodies produce and also something which can affect material bodies.

Transformations of Energy. The most important property of energy is that it cannot be destroyed—it can only be changed from one form to another. By examining some of these transformations of energy, we can learn more about the kinds of energy that are known.

When work (mechanical energy) is used to move a book along a table against the resistance of friction, the work or mechanical energy is changed into heat energy. *Work done against friction is always turned into heat.* Whenever you strike a match, you are making use of such a conversion of mechanical energy into heat by means of frictional resistance.

The motion of electrons is *electrical energy.* In the electrical generator, mechanical energy is used to turn the generator, and this mechanical energy appears at the terminals of the generator as electrical energy—a flow of electrons through a conductor.

In the storage cell, electrical energy is sent into the cell during charging, and apparently disappears. Actually it has been stored in the cell in the form of *chemical energy*—the energy of chemical reactions. When the cell is connected to a circuit and allowed to discharge, the chemical energy is turned back into electrical energy.

All forms of energy are interchangeable. Electrical energy is turned into mechanical energy in the motor; into heat energy in a toaster; into light energy in the incandescent lamp; etc. Heat energy is converted to mechanical energy in steam and gasoline engines; to electrical energy in the thermocouple. Light is changed to chemical energy in photography; to electrical energy in the photoelectric cell; to mechanical energy in the radiometer. Chemical energy is transformed to mechanical energy in explosions. Each form of energy can be changed to any of the other forms, and during these changes there is no loss of energy. *A definite amount of one form of energy is exactly equivalent to a definite amount of each of the other forms.* For example, when work is changed to heat, 1 B.T.U. of heat is obtained for every 778 foot-pounds of work; and when heat is changed to work, 778 foot-pounds are obtained for every B.T.U. of heat. This is known as the law of conservation of energy.

Energy Waste. While energy is never *destroyed* during transformations, some energy is often *lost* or *wasted* in forms which are not useful at the moment. For example, in the electrical generator, it would be desirable to change all the mechanical energy supplied into electrical energy. Unfortunately, some of this energy will be changed into heat instead, as a result of friction of the moving parts (work done against friction is always changed to heat). This heat is useless, since it does nothing but raise the temperature of the generator and finally escape by conduction and radiation to the air. As a result, the efficiency of the energy conversion (in terms of useful output) is never perfect (100%). One of the engineer's problems is to reduce this friction loss, and other similar losses which occur, in order to obtain a maximum of useful energy output from the energy input.

One of the chief causes of energy loss in electrical devices is the heating effect of a current. As will be explained later, an electric current always produces heat in every conductor through which it flows. Except where heat is deliberately wanted (toasters, irons, heat lamps), this generated heat represents a waste of energy. It occurs unavoidably in motors, generators, power transmission lines, transformers, etc., in every case reducing the efficiency of the device and representing increased cost to the consumer. Such losses, fortunately, can be kept relatively low—just a few per cent of the total energy involved—so that electrical machines are the most efficient machines known.

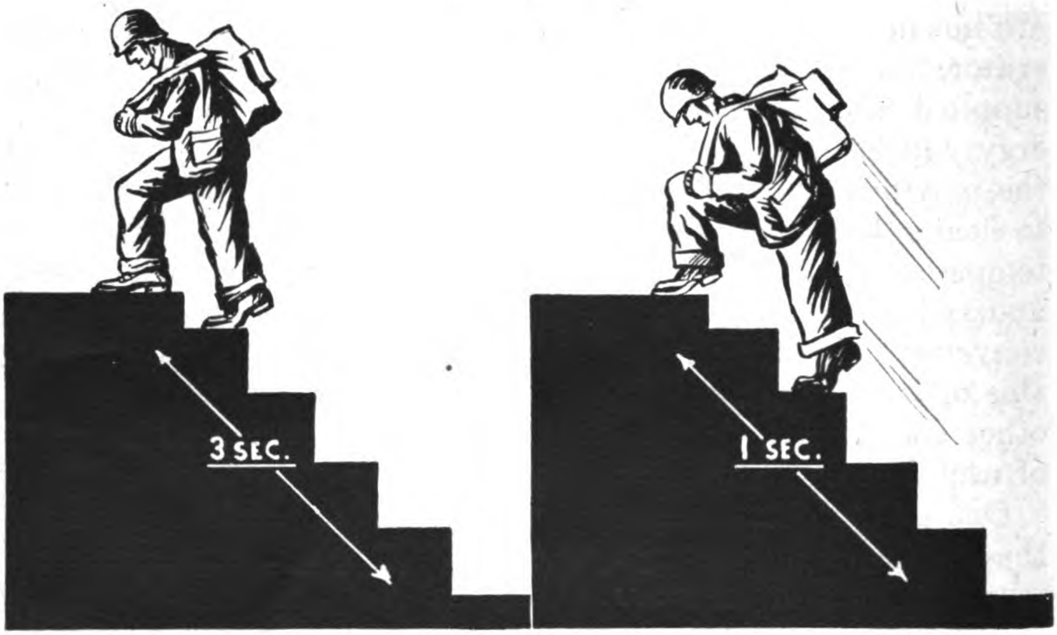
POWER

Power. Suppose an excavation can be dug by one worker in 60 days, or by two workers in 30 days, or by a steam shovel in 1 day. In each case, the same amount of work is done. *Time* does not enter into calculation of the *amount* of work done.

Power is the term which takes into account the time element or the *rate* at which work is done. *Power is the rate of doing work, or the rate of transforming or transferring energy.* Power is expressed as the amount of work done per unit of time (usually 1 second or 1 minute).

$$\text{power} = \frac{\text{work}}{\text{time}} = \frac{\text{force} \times \text{distance}}{\text{time}}$$

$$P = \frac{W}{t} = \frac{FD}{t}$$



Power. At the left the soldier climbs the stairs in 3 seconds; at the right, he climbs them in 1 second. In each case he does the same amount of work; on the right, however, he develops three times as much power as on the left, because the work is performed in one third the time.

If we say that an electric hoist did 20,000 ft-lb of work in lifting a 2000-lb load to a height of 10 ft, we are stating only how much work was accomplished. But if we add that the time required was 16 sec, we can compute the power of the machine:

$$P = \frac{W}{t} = \frac{20{,}000 \text{ ft-lb}}{16 \text{ sec}} = 1250 \, \frac{\text{ft-lb}}{\text{sec}}$$

When comparing machines, then, we need a unit that will indicate how fast they can perform the tasks for which they were designed. If one machine does the same amount of work in less time than another, the faster machine is said to develop more power; if it completes the task in one-half the time needed by the second machine, it develops twice as much power.

Units of Power. The horsepower (HP) is the unit commonly used to express the power ratings of most types of machinery, including steam engines, gas engines, and some electric motors. *One horsepower is equal to 33,000 ft-lb of work per minute, or 550 ft-lb per second.* To calculate the HP rating of a machine, divide the power developed in ft-lb per min by 33,000, or the power in ft-lb per sec by 550.

$$\text{HP} = \frac{\text{ft-lb per minute}}{33{,}000} = \frac{\text{ft-lb per sec}}{550}$$

Steam engines may develop several hundred horsepower. The horsepower of modern automobile engines may reach 100 or more. The type of engine used in the Flying Fortress develops 125 HP per cylinder; each 18-cylinder engine develops about 2200 HP, and the four engines give a total of 8800 HP.

For describing electric motors and other electrical appliances, the power units commonly used are the *watt* and the *kilowatt.*

The Watt. The power in an electric circuit can be found by multiplying the voltage drop across the circuit by the current flowing through it. If the voltage is measured in volts, and the current in amperes, the calculated power is in *watts. One watt of power results when one ampere of current flows under the action of one volt of emf.*

You may wonder why multiplying volts by amperes gives power, when power is supposed to be a rate of doing work or converting energy. If you recall what each of these units represents, you will see why the result is power. One ampere is a *rate of flow* of electrons—a certain number of electrons flowing past a point each second. One volt is a certain difference of electrical pressure. Therefore one watt is equivalent to a certain number of electrons moving through a certain difference of potential each second.

This is the exact equivalent of a certain number of pounds of coal being raised through a certain number of feet each second. In both cases we have power—a rate of doing work. (Remember that it takes work to move an electron through an electric field.) Therefore we are quite correct in writing the following formula:

$$\textbf{electrical power (in watts)} = \textbf{volts} \times \textbf{amperes}$$
$$W = EI$$

The Kilowatt. For measuring large amounts of power, the kilowatt (equal to 1000 watts) is frequently used. The power output of generators is usually expressed in kilowatts.

The Wattmeter. Power in electric circuits may be found by measuring the voltage with a voltmeter and the current with an ammeter, and then multiplying the readings. The wattmeter is a single instrument which does this automatically. It contains two coils instead of one. One coil is a high-resistance coil corresponding to a voltmeter coil; the other is a low resistance coil corresponding to an ammeter coil. The voltmeter coil is free to rotate, and is mounted so that it will turn as the result of electromagnetic attraction between the two coils.

The voltmeter coil is connected across the circuit, as any voltmeter would be connected; the ammeter coil is connected in series with the circuit. The magnetic strength of each coil is proportional to the current in it, and hence the force of attraction between the two coils will depend on the product of voltmeter and ammeter currents. For example, *doubling the voltage* would double the voltmeter current, double the force of attraction between the coils, and hence *double* the reading of the wattmeter. *Tripling the current* would similarly *triple* the reading. Doing both together—doubling the voltage and tripling the current—would multiply the reading by 6.

Other Formulas for Electrical Power. We have already seen that power is given by the formula,

$$W = EI$$

By Ohm's law, $E = IR$; substituting for E in the above formula, we obtain:

$$W = (IR)I = I^2R$$

That is, the power in a circuit is equal to the square of the current multiplied by the resistance of the circuit.

Also by Ohm's law, $I = \frac{E}{R}$. Substituting again, we have:

$$W = EI = E\left(\frac{E}{R}\right) = \frac{E^2}{R}$$

That is, the power in a circuit can also be found by dividing the square of the voltage by the resistance.

Sometimes one of these formulas is easier to apply than the others for the particular information given in a problem; we select the most convenient of the three formulas for each problem.

Electrical Energy. Power is important in electrical devices as it indicates the rate of use of electrical energy. But it is the total energy used which must be paid for, not the rate of use. To operate a 100-watt lamp for one hour is going to cost 60 times as much as operating the lamp for one minute, since 60 times as much energy is consumed (transformed into light and heat) in the former case.

This example indicates that the total amount of energy used can be found by multiplying the power by the time. If a 100-watt lamp uses a certain amount of energy each hour, multiply the rate by the number of hours to find the total energy. Electrical energy is measured in *watt-hours;* one watt-hour is the energy used in one hour by a device whose power consumption is one watt.

energy (in watt-hours) = watts × hours

Since *watts* = *volts* × *amperes,*

watt-hours = volts × amperes × hours

watt-hours = EIt

A more common unit is the kilowatt-hour (equal to 1000 watt-hours). Energy in kilowatt-hours is given by the following formula:

$$\text{KWH} = \frac{EIt}{1000}$$

where t must be measured in hours.

TYPICAL PROBLEMS

Three 60-watt lamps are burned for 4 hours. (*a*) How many kilowatt-hours of energy are used? (*b*) What is the cost of operation at 6¢ per kilowatt-hour?

$$(a)\ \text{KWH} = \frac{\text{watts} \times \text{hours}}{1000} = \frac{(3 \times 60) \times 4}{1000} = \mathbf{0.72\ KWH}$$

$$(b)\ \text{Cost} = \text{KWH} \times \text{rate} = 0.72 \times 6 = \mathbf{4.3¢}$$

A home refrigerator, operating on 110 volts, draws a current of 3 amperes. If the motor runs 6 hours a day, and the cost is 5¢ per KWH, what is the daily cost of operation?

$$\text{KWH} = \frac{EIt}{1000} = \frac{110 \times 3 \times 6}{1000} = 1.98\ \text{KWH}$$

$$\text{Cost} = \text{KWH} \times \text{rate} = 1.98 \times 5 = \mathbf{9.9¢}$$

HEATING EFFECTS OF THE ELECTRIC CURRENT

Heat in Electric Circuits. We have just seen how the electrial energy flowing into an electric circuit can be calculated on the basis of the voltage, current, and time. We know that this electrical energy does not disappear, but is converted to some other form of energy by the devices in the circuit. Motors (to be considered in a later chapter) convert the electrical energy to work; storage cells as we have seen convert it to chemical energy; *resistances in the circuit convert the electrical energy to heat.* We will now consider applications of this last-named effect—the conversion of electrical energy to heat by resistances.

Electrical Equivalent of Heat. Experiments have shown that for every watt-second of electrical energy flowing into an electrical resistance, 0.24 calories of heat are produced. This is called the electrical equivalent of heat, and is expressed in the following formula:

$$\mathbf{H\ (calories) = 0.24\ watt\text{-}seconds}$$

$$H = 0.24\ I^2Rt$$

where I is the current through a resistance, R is the resistance in ohms (I^2R is the power in watts), and t is the time in seconds during which the current flows.

Note that, in place of the quantity, I^2R, in the above formula, we could have used either of its equivalents, E^2/R or EI. For calculations in series circuits, where the current is more often known than the voltage, the formula as given is most convenient.

Distribution of Heat in Circuits. In a *series* circuit, containing several resistances, the current through each resistance is the same. From the formula it is at once evident that most heat will appear in the greatest resistance. Thus in an electric lamp circuit, the high resistance filament gets white hot, while the low resistance wires in the lamp cord remain cool. However, if the total resistance of the circuit is *reduced, more* heat will be generated than before, since heat is proportional to E^2/R, and E remains constant. When a short circuit occurs, the resistance is greatly reduced, and the greatest amount of heat is generated; on the contrary, adding another device (such as a toaster) in series with a lamp would result in both devices being relatively cool.

In actual practice, all electrical devices in the home are operated in *parallel*. Each device acts as though it were the only one connected to the line, and is not affected by the others. Hence it can be seen that the device with the lowest resistance will be the one generating the most heat. The larger the power rating of a lamp, for example, the thicker the filament is, in order to provide lower resistance.

Heat and Temperature in Electrical Devices. It must not be assumed that the generation of a large amount of *heat* automatically means a high *temperature* for that part of a circuit. The filament of a 200-watt lamp has a resistance of 50 ohms and carries 2 amperes of current. It gets white hot. 8000 feet of No. 18 copper wire also has a resistance of 50 ohms, and if placed in the circuit instead of the lamp would carry the same current and generate the same amount of heat. Yet the copper wire would remain cool. The reason for this is that the heat in the copper wire is spread out over 8000 feet of wire, while in the lamp filament it all appears in a few inches of wire. In dissipating ("getting rid of") all this heat, a few inches of wire will become white hot.

Thus it is the *concentration of heat* which determines the temperature of a resistance, not the total amount of heat generated. For that reason, resistors must not only be marked with the amount of resistance they contain, but also with the power (rate of heat generation) that can be dissipated at a safe temperature.

A 2000-ohm, ¼-watt resistor has 2000 ohms, but must not be operated with more than ¼ watt flowing through it. A 2000-ohm, 5-watt resistor, also has 2000 ohms, but can safely carry 5 watts. Can you calculate how much *current* each resistor can safely carry? (Use formula, $W = I^2R$.)

TYPICAL PROBLEM

(*a*) How much current will a 22-ohm electric iron draw when connected across a 110-volt line? (*b*) At what rate is energy used? (*c*) How many calories of heat are developed in 10 minutes?

(*a*) From Ohm's law, $I = \frac{E}{R}$; $I = \frac{110}{22} =$ **5 amperes**

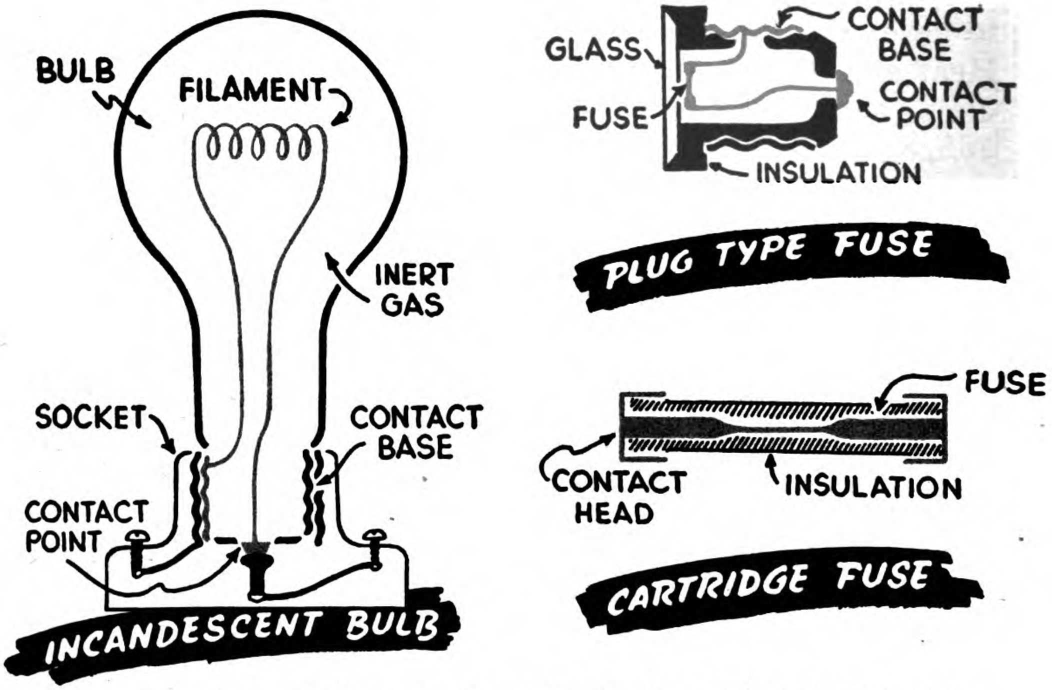
(*b*) $W = EI$; $W = 110 \times 5 =$ **550 watts**

(*c*) $H = 0.24\, I^2Rt$

$H = 0.24 \times 5 \times 5 \times 22 \times 600$

$H =$ **79,200 calories**

Applications of the Heating Effect of the Current. *The incandescent lamp.* The incandescent electric lamp is essentially a fine

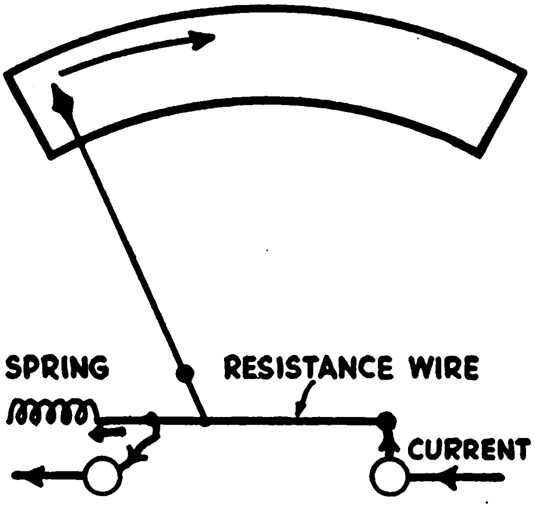


Applications of the Heating Effect of an Electric Current

wire with a high melting point, sealed in a glass envelope (bulb) in which provision is made to prevent oxidation when the passage of current heats the filament (wire) to incandescence. Early lamps contained a high vacuum, but modern lamps are usually filled with a mixture of argon and nitrogen. This gas mixture not only prevents oxidation of the tungsten filament, but also retards its evaporation. Evaporation of the tungsten filament during incandescence tends to destroy the filament and blacken the bulb. Modern gas-filled tungsten lamps of the type ordinarily used for home lighting develop about 1⅓ candlepower per watt, as contrasted with the early carbon filament lamps which gave about ⅓ candlepower per watt.

The fuse. A fuse is usually a strip of metal having a low melting point and fairly high resistance per unit length. Fuses are constructed to melt when more than the desired current passes through them; for example, a 10-ampere fuse melts when the current through it exceeds 10 amperes. Electrical meters and other devices are frequently protected from the effects of excessive currents by means of properly selected fuses. House circuits are commonly protected by 15-ampere fuses. Fuses are always connected in series. Consequently, when a fuse "blows," it opens the circuit and no current will flow until the fuse is replaced.

The hot-wire ammeter. The hot-wire ammeter makes use of the expansion (increase in length) which occurs when a wire is heated. As the diagram shows, the working element of the meter is a short piece of resistance wire, fastened at one end and held taut by a spring attached to the other end. When current passes through the wire, it is heated and expands, causing the pointer to move over a scale. The amount of expansion, and hence the reading, depends on



The Hot-Wire Ammeter. When current flows through the resistance wire, the wire is heated and expands. The free end of the wire is pulled to the left by the spring, and the pointer moves to the right.

the size of the current flowing; therefore the device can be used as an ammeter. This meter can be used on AC or DC current, and is especially useful for high frequency radio circuit measurements because of its almost complete lack of inductance (page 108).

The arc lamp. An arc light consists essentially of two carbon rods with a potential difference of about 50 volts (preferably DC) between them. When the rods are touched together for a short time carbon vapor is formed from the great heat. If the rods are then separated slightly, current continues to flow through the surrounding vapor, furnishing an intense white light. The carbon arc light reaches a temperature of more than 3000°C. The efficiency of the arc light is about 2 candlepower per watt, but it is too brilliant and too hot for use in ordinary lighting. Its principal uses today are in motion picture projectors, theatrical lighting, and Army and Navy searchlights.

Electric furnaces. One type of industrial electric furnace operates on the resistance principle. If a material is to be melted, for example, and it is a conductor of electricity, it is put into a suitable vessel and a large current is passed through it. Heat produced by the overcoming of resistance causes melting. If the material is a non-conductor, it may be packed around a carbon core through which the current passes. The carbon core gets hot and heats the material. The material may also be put into a vessel which, in turn, is placed inside the coils of the furnace, the coils being of resistance wire wound on a core having a high-melting point.

In the arc furnace, temperatures around 3500°C can be obtained. A heavy current passing between very large carbon electrodes is arranged to heat the material to be melted.

COMPLETION TEST

Whenever a force overcomes a resistance through a distance, ___(1)___ is accomplished. This is one form of energy called _______(2)_______ energy. There are other forms of energy, such as the energy of electrons in motion, or _______(3)_______ energy. All forms of energy can be _______(4)_______ into other forms. Energy cannot be destroyed, but it can be wasted; in electrical circuits, the chief cause of energy loss is _______(5)_______ of the conductors. The rate at which energy is transformed or transferred is called _______(6)_______. One horsepower is equivalent to _____(7)_____ foot-pounds of _____(8)_____ performed each second. The electrical unit of power is the ____(9)____, which is equivalent to ________(10)________ amperes of current flowing through a potential drop of ________(11)________ volts. We pay for electrical energy on the basis of number of ________(12)________ consumed. Electrical appliances for the home require more power the (*greater*, *smaller*) ________(13)________ their resistance. Electrical energy in resistances is changed into ________(14)________. This effect is (desirable, undesirable) ________(15)________ in lead-in wires, and is ________(16)________ in electric lamps.

QUESTIONS

1. Does the amount of power supplied by an engine or generator depend on the length of time it operates? Does the amount of energy supplied?

2. Name a device which transforms (*a*) mechanical energy to electrical energy; (*b*) electrical energy to chemical energy; (*c*) mechanical energy to heat energy (deliberately); (*d*) heat energy to electrical energy.

3. What energy transformation occurs (*a*) in a motor; (*b*) in burning coal; (*c*) in a muscle; (*d*) in a metal stamping or punching operation.

4. How can electrical power be measured without a wattmeter? How does a wattmeter perform this measurement?

5. How do fuses act as safeguards against the effect of short circuits?

6. Is it advisable to use a 30-ampere fuse in a 20-ampere circuit? Why?

7. Describe the construction and operation of a modern incandescent lamp. Why don't the lead-in wires get as hot as the filament?

8. How does the hot-wire ammeter work? What are some of its advantages and disadvantages?

9. How does an arc lamp work? What are some uses for arc lamps today?

PROBLEMS

1. How much work can an 8 HP engine do in 2 minutes?

Ans. 528,000 ft-lb

2. A hoisting engine lifts a 1 ton rock a distance of 11 feet in 10 seconds. (*a*) How much work does it do? (*b*) What horsepower is expended?

Ans. (a) 22,000 ft-lb (b) 4 HP

3. How long will it take a 10 HP engine to lift an 1100 lb weight a distance of 50 ft?

Ans. 10 sec

4. An incandescent lamp draws 0.8 amp when connected to a 120-volt line. Calculate (*a*) the wattage, (*b*) the resistance of the lamp.

Ans. (a) 96 watts (b) 150 ohms

5. The label on an electric toaster reads, "550 watts; 110 volts." (*a*) What current does the appliance draw? (*b*) What is its resistance?

Ans. (a) 5 amp (b) 22 ohms

6. Radio resistors made of carbon are available in ½-, 1-, and 2-watt sizes. What (*a*) resistance, (*b*) wattage rating should a resistor have if it is to carry 5 mils at 100 volts? (*c*) What size resistor would you select if they are to be operated at only about 50% of capacity?

Ans. (a) 20,000 ohms (b) ½-watt (c) 1-watt

7. Calculate the calories of heat developed in 15 min by the electric toaster in problem 5. Ans. 119,000 cal

8. A 120-volt house circuit has a 15-ampere fuse. How many 60-watt lamps in parallel can be operated at once without blowing the fuse?

Ans. 30

9. What is the cost of operating each of the following appliances for 120 hours at 8 cents per KWH: (*a*) 100-watt lamp; (*b*) the toaster in problem 5; (*c*) an electric soldering iron of 20 ohms resistance connected to a 110-volt line. Ans. (a) $0.96 (b) $5.28 (c) $5.81

10. The motor of an electric refrigerator operated on a 110-volt line draws a current of 2.5 amp. To maintain the desired temperature inside the refrigerator, the motor operates ⅓ of the time. What is the power of the motor (*a*) in watts, (*b*) in horsepower? (*c*) Calculate the apparent resistance of the motor. (*d*) What will be the cost of operating the refrigerator for 30 days if the rate is 5¢ per KWH?

Ans. (a) 275 watts (b) 0.369 HP (c) 44 ohms (d) $3.30

SEVEN— INDUCED EMF; GENERATORS AND MOTORS

MAGNETISM IN MOTION PRODUCES ELECTRICITY

Electrical Equivalent of Work. As explained previously, work and electricity are simply different forms of energy. It has been found that one horsepower (which is a rate of doing work) is exactly equivalent to 746 watts (a rate of flow of electrical energy). That is, 550 ft-lb can be turned into 746 watt-seconds, and vice versa.

In this chapter we will consider the practical methods of changing work into electrical energy (the electric generator), and methods of changing electrical energy back into work (the electric motor). Both the generator and the motor make use of the relationships which exist between magnetism and electricity.

Faraday's Discovery. The development of the voltaic cell made it possible for scientists to experiment with and study electric currents, but voltaic cells could not furnish sufficient power to make possible the widespread use of electricity as of today. The production of large amounts of electric power had to await the development of the mechanical generator, that is, a device which can transform mechanical energy (or work) into electrical energy. The underlying principle of the generator was discovered by Michael Faraday, the renowned English scientist.

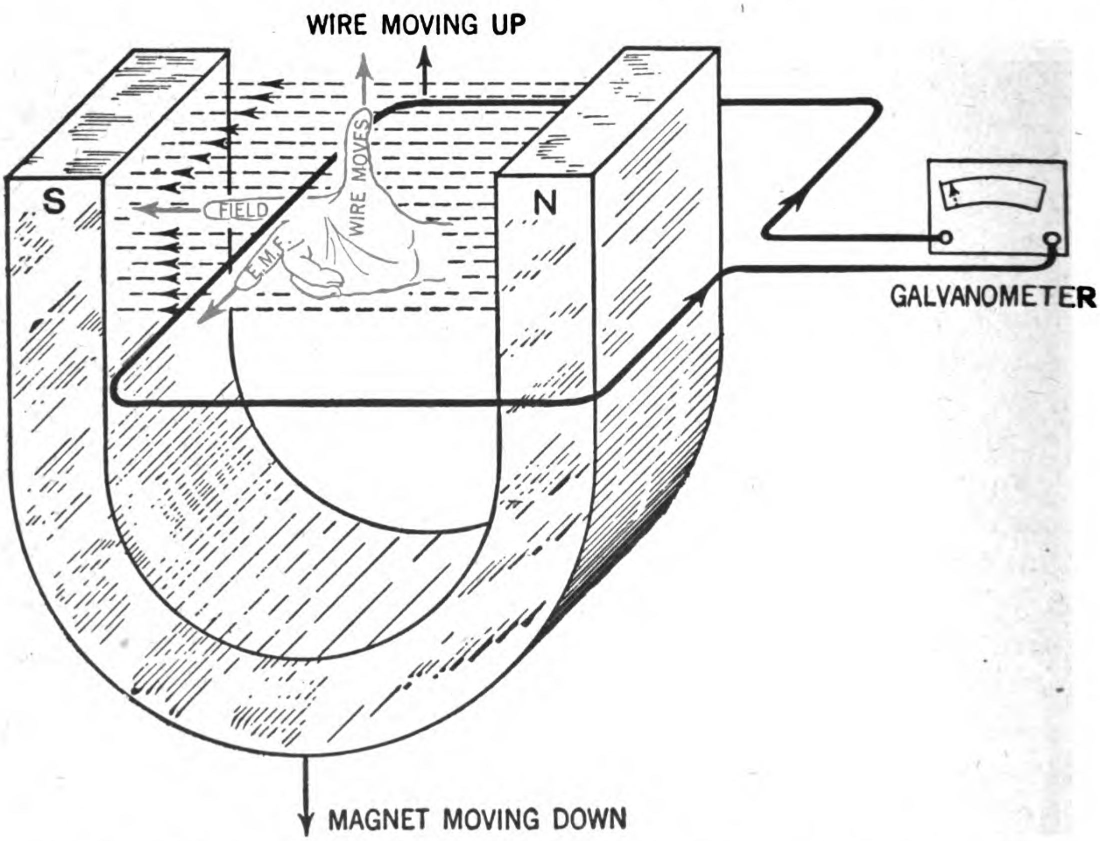
Faraday wondered, "If electricity can produce magnetism, can magnetism produce electricity?" By 1831, he had discovered that there is a flow of current whenever a bar magnet is *moved* in or out of a coil of wire, the ends of which are connected to form a closed circuit. The weak current can be detected by connecting the ends of the wire to a galvanometer.

The emf which makes this current flow is termed an *induced emf,* and its production, being dependent upon magnetism, is called *electromagnetic induction.*

Joseph Henry, in America, independently made many of the same discoveries as Faraday. These two scientists receive full credit for discovering the fundamental principles of electromagnetic induction, upon which our present electrical age is founded.

Production of an Induced EMF. The experiments of Henry and Faraday revealed that *an emf is induced in a conductor whenever a magnetic field and the conductor move with respect to each other in such a manner that magnetic lines of force are cut.* The conductor can move through the magnetic field, or the magnetic field can move past the conductor—it makes no difference. But no emf is induced when the conductor moves parallel to the lines of force, or is held stationary with respect to the field.

Magnitude and Polarity of Induced EMF. *The magnitude of the induced emf depends upon the rate at which magnetic lines of force are cut.* The number of lines of force cut per second, and hence the induced emf, may be increased in three ways: (1) by increasing the strength (intensity) of the magnetic field; (2) by increasing the speed at which the conductor or the magnetic field moves; (3) by increasing the number of loops or turns of wire in



Fleming's Rule for Determining the Direction of an Induced EMF the conductor. The magnitude of the current (termed the *induced* current) that flows in the circuit as a result of the emf produced depends, of course, on the resistance of the circuit; that is,

$$I = \frac{E}{R}.$$

The direction of the induced current may be determined by the *right-hand three-finger rule* (Fleming's Rule): *extend the thumb, forefinger, and center finger of the right hand at right angles to each other. If the thumb points in the direction in which the conductor moves through the field, and the forefinger points in the direction of the magnetic lines of force (toward the south pole), then the center finger points in the direction of the flow of current in the conductor.*

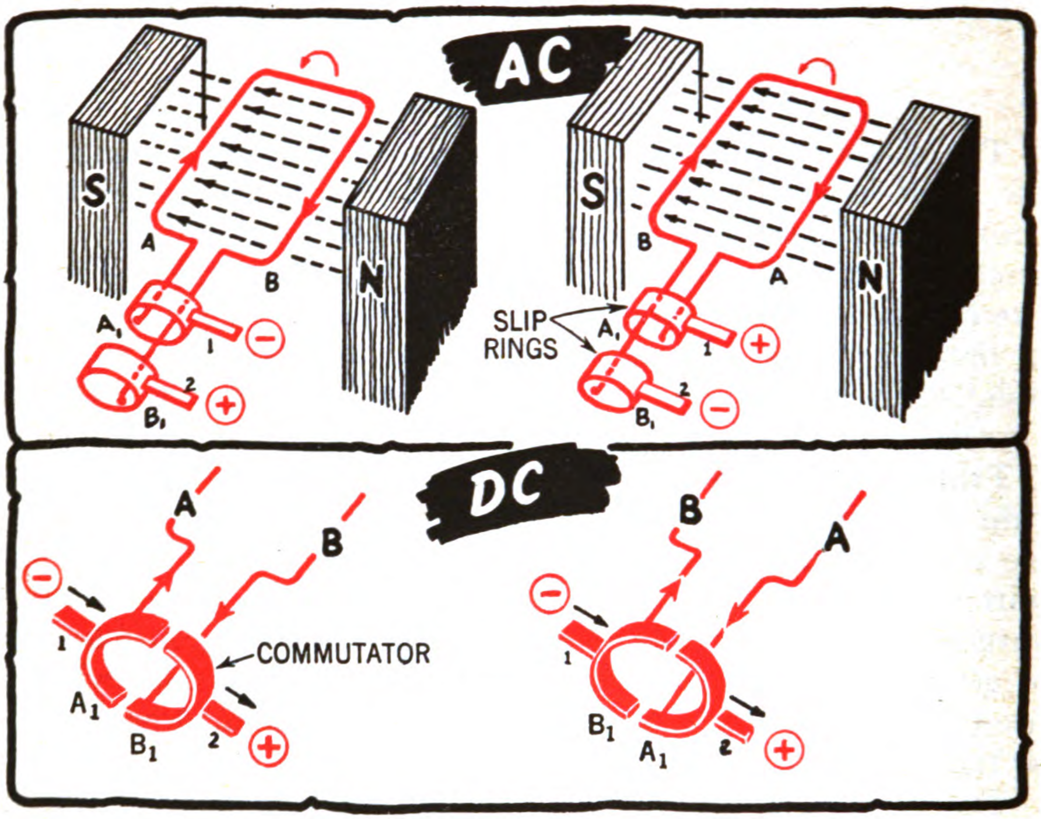
Principle of the AC Generator. It is apparent from Fleming's rule that if we change the direction in which the conductor moves, we also change the direction of the current. Moving a straight wire up and down so that it cuts magnetic lines of force produces surges of current that *alternate* in direction. The practicable way of generating continuous alternating currents of electricity is the use of a rectangular loop of wire (*armature*) mounted on an axis so that it can be rotated in a magnetic field.

The method of introducing current into the outside circuit consists of connecting the ends of the wire in the armature to two *slip rings* upon which two *brushes* (metal or carbon) rest. Since each brush makes constant contact with the same slip ring, the current in the outside circuit alternates in step with the alternations in armature. (See diagram on page 94.)

Alternating currents are treated more fully in Chapter 9.

The DC Generator. The simple DC generator is identical in construction with the AC machine, except that the slip rings are replaced by a *split-ring commutator.* The action of the commutator may be understood from the diagram on page 94. Brush 1 always makes contact with the side of the loop moving downward, and brush 2 with the side moving upward. In this way, the current is kept flowing to the outside circuit in one direction, even though the current in the armature is alternating.

By using more coils set at angles to each other in the armature so that some coil is always cutting lines of force at the maximum rate, a more even flow of current results. Each coil contributes its share of current (through its own pair of segments) at regular intervals.



In the top diagram (left) illustrating the action of the AC generator, coil side *B* moves up through the magnetic field. According to Fleming's rule, an emf is induced in the direction shown; brush 2 is therefore +. Conversely, brush 1 is −. As the coil rotates in the counterclockwise direction shown in the right-hand side of the drawing, coil side B moves downward through the magnetic field, thus reversing the direction of the emf induced. Since side *B* is connected with slip ring B_1, which is in turn connected with brush 2, brush 2 is now −, while brush 1 becomes +.

In the DC generator, the direction of the emf alternates in the rotating coil just as it did in the AC generator. However, the polarity of the brushes in the DC generator does not alternate. This is accomplished by substituting a split commutator for the slip rings. Thus, when coil side *B* is moving up, its commutator segment (B_1) makes contact with brush 2, which becomes +. When coil side *B* moves down (thus reversing the direction of the emf), its commutator segment rotates and now makes contact with brush 1, which remains −.

Lenz's Law. An important characteristic of induced currents is demonstrated by the experiment illustrated on page 96.

The facts illustrated in the diagram are summarized in Lenz's law, stated as follows: *an induced current always flows in such a direction that its magnetism opposes the motion or the change that induced it.* There are many applications of Lenz's law, especially in connection with alternating currents.

CONSTRUCTION OF GENERATORS

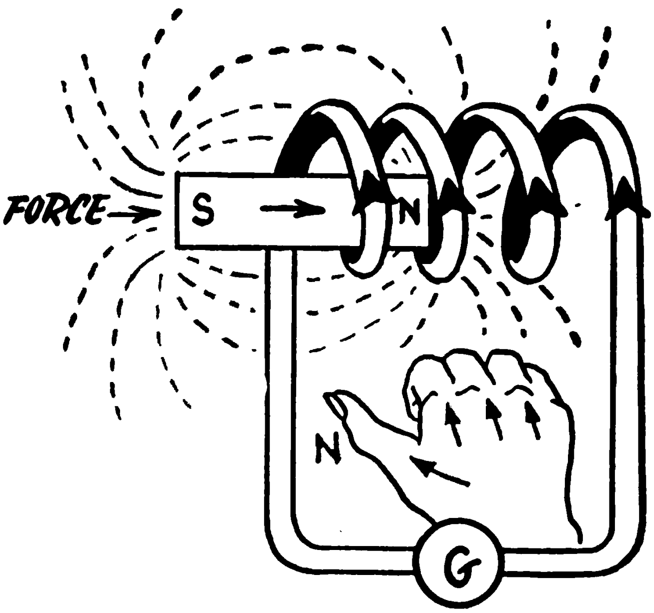
Magnetic Fields for AC Generators. In the explanation of the AC generator, it was assumed that the magnetic field was supplied by a *permanent magnet.* Generators which are actually constructed with permanent magnets are called *magnetos;* they are used frequently in the ignition systems of gasoline engines (see page 113). However, permanent magnets cannot provide a strong enough field for large power generators, and, besides, cannot have their strength controlled. For these reasons, most generators contain *electromagnets* to produce the necessary magnetic field.

In actual construction, these magnets are built in the form of a continuous ring, with two or more poles attached on the inner surface and projecting into the space inside the ring. Each pole has a coil of wire wound around it, and current flowing through this coil magnetizes the pole. In a two-pole magnet, the coils are wound so that the poles have opposite polarity. This entire structure is called the *field structure* of the generator; the coils are called *field windings.*

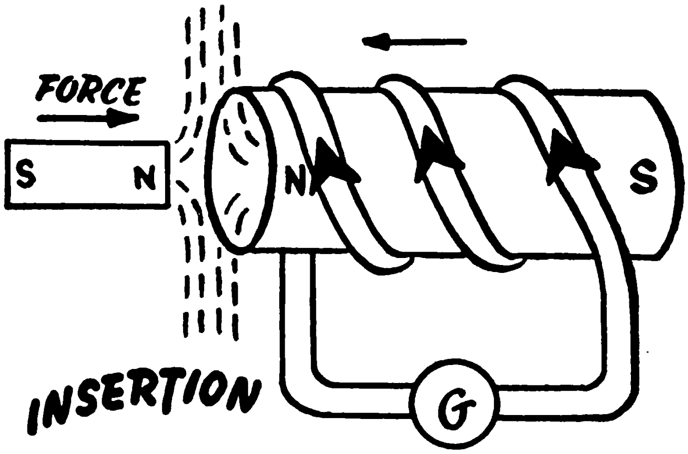
Supplying Current for AC Generator Fields. In order for the generator to operate, the polarity of the field must remain constant. Hence a source of direct current is needed for the field windings. This current may be supplied by a storage battery, or by an auxiliary DC generator. In either case, the power required by the field windings is just a small fraction of the total power which the AC generator develops.

The Armature. The armature of a generator is the rotating coil or sets of coils in which the current is generated. In actual construction, the armature coils are mounted in slots running along the outside of a cylindrical drum of soft iron. This drum rotates inside the ring-like field structure, and carries the coils through the magnetic field.

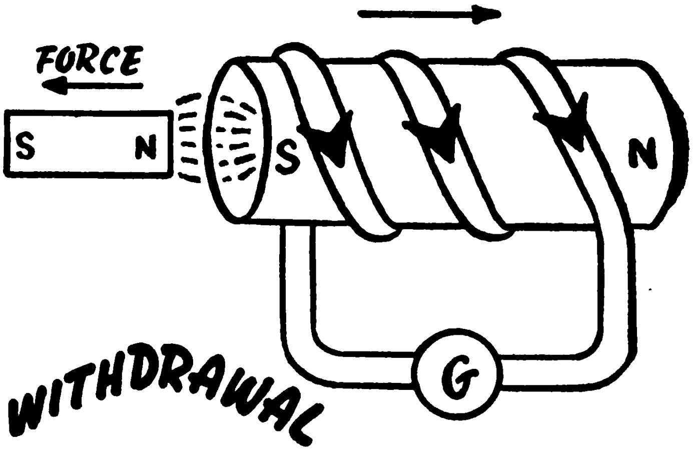
As the magnetic lines of force of the bar magnet cut the coil, a current is induced in the coil in the direction shown by the arrows. This induced current sets up its own magnetic field. Applying the right-hand rule, we find that this field has a north pole on the left.



Since like poles repel each other, the two magnetic fields oppose the approach of the coil and magnet. Force is required to overcome this mutual repulsion of magnet and coil.

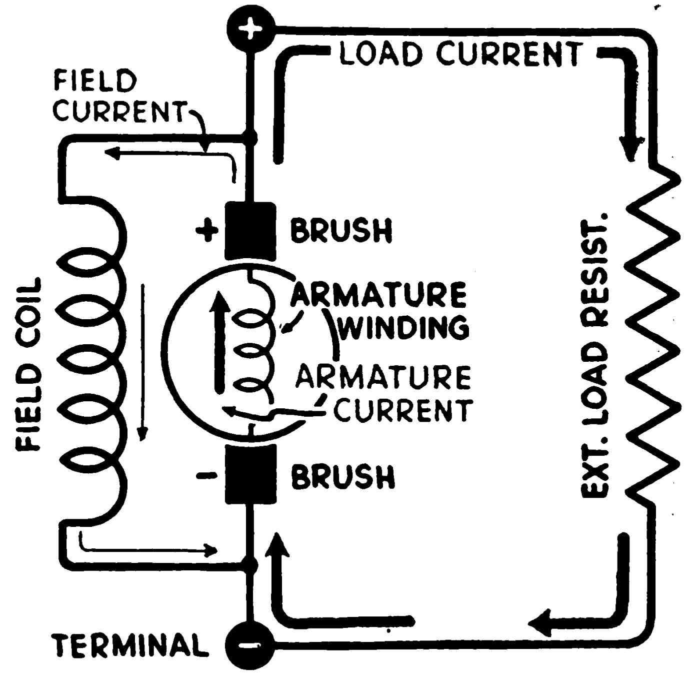


When the magnet is withdrawn from the coil, the direction of induced current reverses, which consequently reverses the polarity of the coil. Since unlike poles attract each other, the two magnetic fields oppose the separation of the magnet and coil.



The drum itself is not solid. It is made up of many thin sheets of iron (circular in shape) which have been placed next to each other on the generator shaft, in this way building up a *laminated* cylinder. The purpose in laminating the armature drum in this way is to prevent the induction and circulation of currents within the iron drum itself. Such currents would heat the drum and would represent a waste of energy. (Note that any induced currents tend to flow parallel to the generator shaft; hence, within the drum such currents would have to jump the many gaps between adjacent laminations. As a result, these so-called *eddy currents* are kept to a minimum.)

Magnetic Fields for DC Generators. As in the case of AC generators, the fields of DC generators are usually provided by electromagnets constructed along similar lines. However, it is not necessary to have a separate source of field current, since the field windings may be connected directly across the terminals of the generator. When part of the output of a generator is used to supply current for the field coils, the generator is said to be *self-excited*. Separate excitation, from storage batteries or auxiliary generators, is, however, sometimes used for DC generators.



The Shunt-Wound DC Generator. The field coils are connected to the brushes in such a way that the generator supplies its own field current, in parallel with its external load circuit. The thickness of the current arrows indicates the relative sizes of the currents flowing.

Voltage Generated by DC Generators. Generators are usually driven by engines of one kind or another—steam engines, turbines, Diesel engines, etc. The speed of rotation of the armature is care-

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fully controlled by a governor which maintains constant speed. Therefore the voltage generated (which depends on the rate at which lines of force are cut) depends only on the strength (number of lines of force) of the magnetic field. The strength of the field depends, in turn, on the amount of current in the field coils. Thus the voltage of a DC generator can be changed by changing the strength of the field current. This is usually accomplished by means of a rheostat in series with the field coils. By adjusting the rheostat, more or less current can be sent through the field windings, and more or less voltage generated in the armature.

"Building Up" the Voltage in the Self-Excited Generator. In the self-excited generator, the field current is supplied by the generator itself. Therefore, when the generator is first started, there is no field current and hence just a slight residual magnetism in the field poles. This small magnetic field induces a small voltage in the armature (a fraction of the normal voltage). This small voltage now sends a small current through the field winding, thereby strengthening the magnetic field somewhat. The strengthened field now produces a larger induced voltage in the armature which in turn increases the field current and magnetic field strength still further. In this way, the magnetic field and the generated voltage slowly build up to their normal values. This process may take as long as 30 seconds in a large generator, and is typical of the situation at the start of any self-excited generator. In separately excited machines, full field strength is present from the beginning, and no build-up period is needed.

Voltage Regulation. A generator, like a voltaic cell, has an internal resistance (the resistance of the armature coils). Hence its terminal voltage is always less than its generated voltage when it is delivering current (see page 56 for discussion of internal resistance). As the load current which the generator is called upon to supply increases, the internal voltage-drop increases and the terminal voltage falls. The amount by which the terminal voltage of a generator drops between the no-current condition and the full-load condition is measured by the *voltage regulation of the machine.* A voltage regulation of 90% means that the voltage at full load is 90% of the voltage at no load.

It is usually desirable to have voltage regulation of 100% or even more (that is, have the terminal voltage rise as the current supplied by the generator increases). This is accomplished by

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means of an auxiliary field winding connected *in series* with the armature and the external load circuit. The load current passes through this auxiliary winding, and adds to the total strength of the magnetizing current. As the generator load current increases, the strength of the magnetic field is increased also by the action of the auxiliary winding. This results in an increase in generated voltage and thus offsets the effect of the increased internal voltage drop. By adjusting the number of turns in the auxiliary winding, it can be made to give any desired amount of voltage regulation, even well above 100%. Such series windings, of course, should have low resistance since they must carry the entire armature current.

Generators of this type are called *compound-wound* generators.

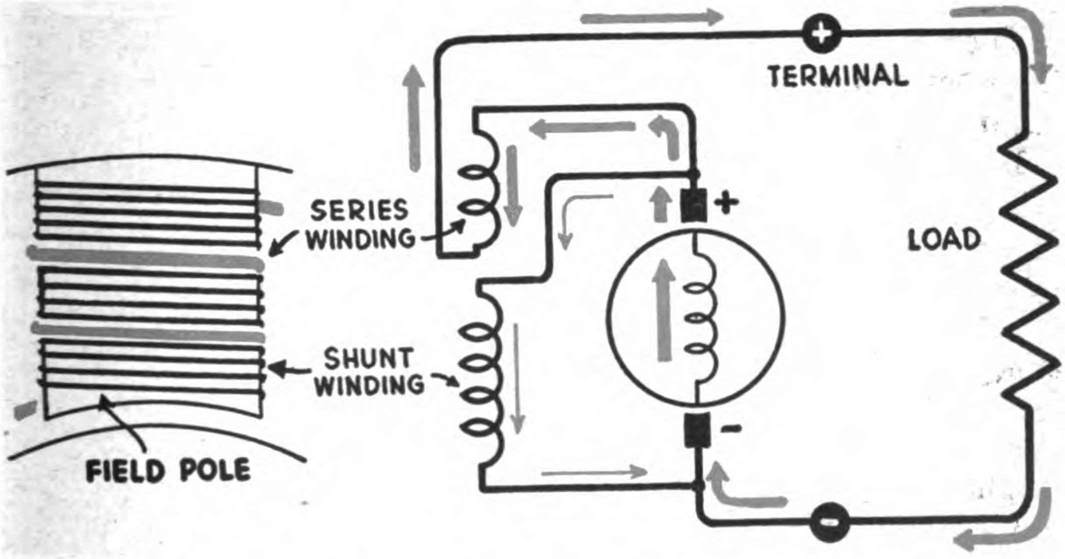


Diagram of the Compound-Wound Generator. The load current flows through an auxiliary series field winding, thus strengthening the field and raising the generated voltage as the load current increases. This offsets the effect of internal voltage drop due to armature resistance.

Multipolar Generators. The voltage generated depends on the rate at which lines of force are cut by the armature. By using several pairs of field poles, instead of just one pair, the armature can be made to cut more lines of force in each revolution, thus generating more voltage at a given speed, or the same voltage at a lower speed. Such multipolar fields have many poles arranged around the main ring, alternating North and South as you pass around the ring. This construction is particularly valuable for slow-speed generators such as are driven by water wheels or reciprocating steam engines.

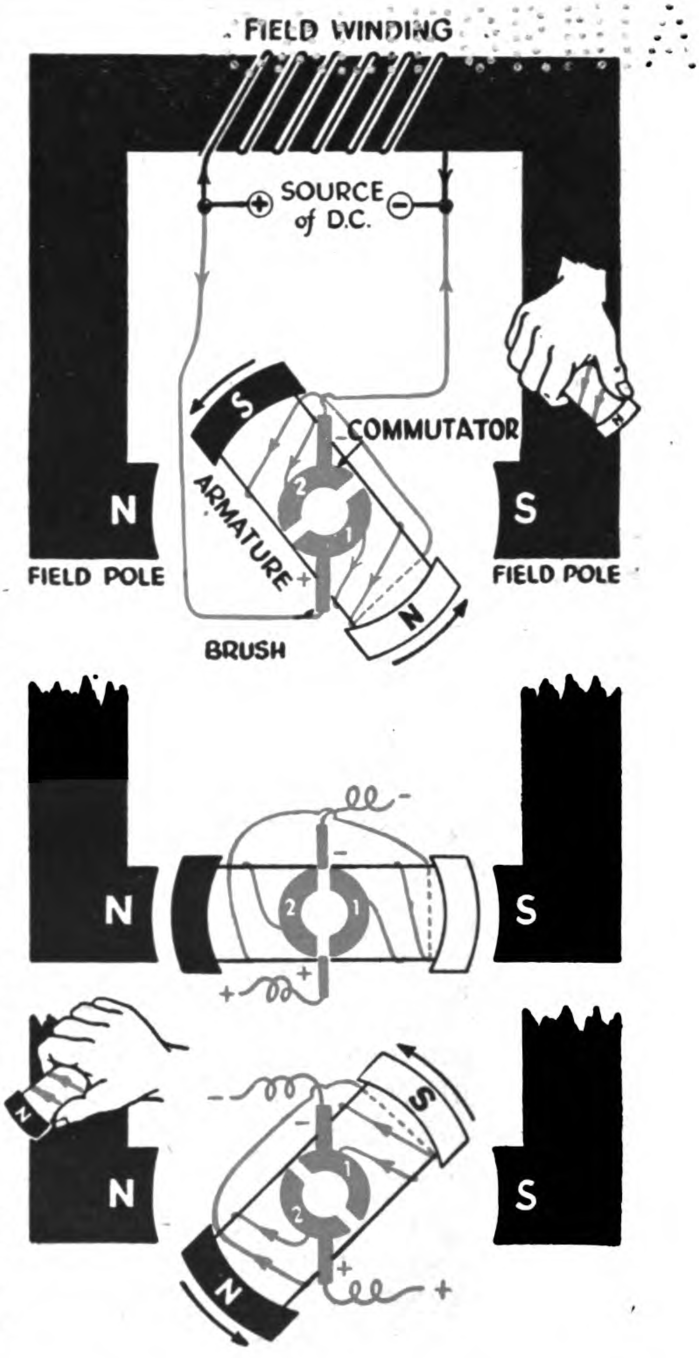
MOTORS

Principle of the Electric Motor. The electric motor is a device which changes electrical energy into mechanical energy, or work. There are many types which vary in structural details, but all operate on magnetic attraction and repulsion.

As shown by the diagram on the next page, the essential parts of the simple motor are: (1) the stationary *field poles;* (2) the *rotating armature;* (3) a split ring, or *commutator,* the segments of which are mounted on the shaft of the motor and insulated from each other; (4) two fixed *brushes* which serve to carry current to the commutator segments, from which it flows through the windings of the armature.

Back EMF of a Motor. Comparison of the DC generator and the DC motor reveals that they are identical in construction. In fact, either is a reversible machine; that is, when mechanical energy forces the armature to rotate against the resistance of the magnetic field, mechanical energy is transformed into electrical energy. When an electric current is sent through the windings of the armature, the armature rotates by reaction against the magnetic field and thus transforms electrical energy into mechanical energy, or work.

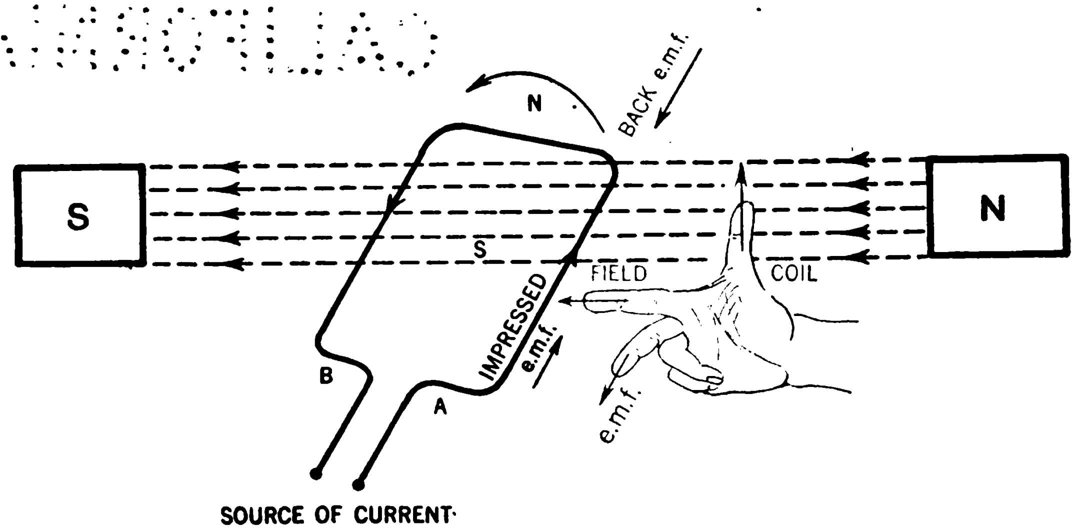
When the machine operates as a motor, its rotating armature still cuts the magnetic lines of force, and will therefore act as a generator and have an emf induced in it. By Lenz's law, this induced emf will tend to oppose the rotation producing it. In other words, the induced emf should oppose the applied emf (which is actually responsible for the rotation). The diagram on page 102 shows that this is actually what occurs. The induced emf is called a *back* or *counter* emf, and it acts to reduce the effective emf driving current through the armature. For example, if a motor is operating on a 120-volt line, and is developing a back emf of 110 volts, the net emf is $120 - 110 = 10$ volts. If the armature resistance is 2 ohms, only 5 amperes will flow through the armature instead of 60 amperes as might at first be expected.



1. Starting with the source of DC, trace the flow of current through the armature from + to —, noting that the current enters segment (1) of the commutator and leaves through segment (2). Applying the right-hand thumb rule to the armature, we find that the white end of the armature is a north pole and the black end is a south pole. The forces of magnetic attraction and repulsion between the poles of the armature and the poles of the field cause the armature to rotate in a counter-clockwise direction.

2. The middle diagram shows that when the armature poles are in line with the field poles, the brushes are at the gap in the commutator and no current flows in the armature.

3. Inertia, however, carries the armature past the field poles as shown in the bottom diagram. In this position, current enters the armature winding through segment (2) and leaves through segment (1), thus reversing the direction of current and hence the polarity of the armature. The black end is now north and the white end is now south. (Compare with top diagram.) The forces of attraction and repulsion again operate to keep the armature rotating in the same counter-clockwise direction.



As the current flows through the coil in the direction of the impressed emf, a magnetic field is set up, the north pole of which is above the coil and the south pole below the coil. Magnetic attraction and repulsion turn the coil in the direction shown. However, as one side of the coil (A) moves up, it cuts the lines of force and an emf is induced in it. As can be seen from Fleming's rule, this induced or back emf is opposite to the impressed emf.

Types of DC Motors. Motors and generators for DC are identical in construction. As in the case of generators, the chief variations in the types of DC motors are related to the ways in which current is provided for the field windings. We will now consider the effects of different field connections.

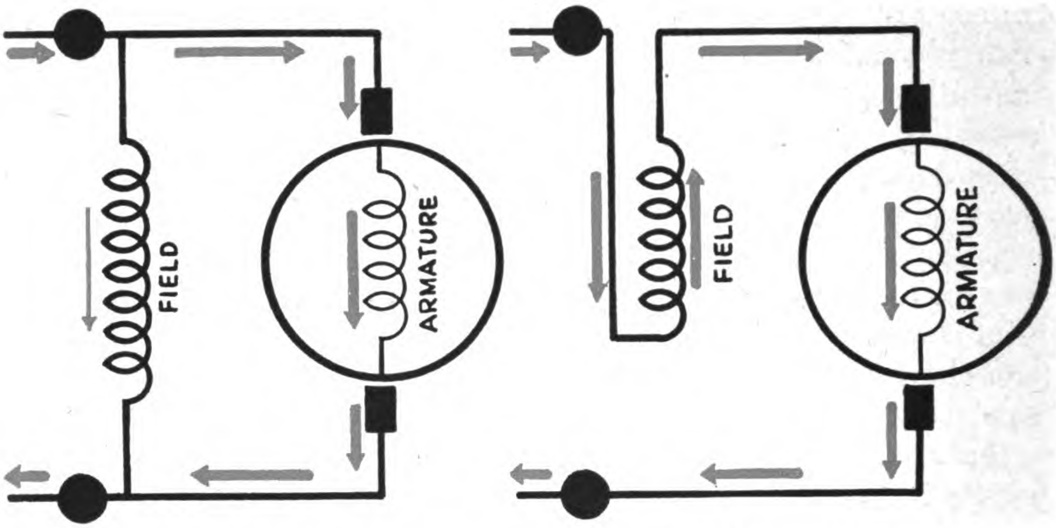
Torque in Motors. As voltage was the important characteristic of generators, so torque (or turning force) is important in discussing motors. The torque of a motor depends on two factors: (1) the strength of the magnetic field; (2) the strength of the armature current. The strength of the armature current is in turn controlled by the amount of back emf generated in the motor. A large back emf reduces the armature current and hence reduces the torque. The back emf, however, depends on the speed of the motor and the strength of the field.

The shunt-wound motor. In the motor diagrammed on page 101, the field is in parallel (or in *shunt*) with the main line. In such a motor, the field strength is independent of anything else happening to the motor, since the line voltage remains constant. The effect of this construction is to produce a motor which has a fairly constant speed under normal conditions. This is explained as follows.

Suppose the motor is driving a machine and an increased load is suddenly applied to the machine (for example, a punch press just as it begins to cut through the material being stamped). This results in an increased torque on the motor shaft, and the motor begins to slow down. As soon as it does, however, the induced back emf becomes less, the armature current rises, and the torque developed consequently increases. The motor continues to lose speed until the armature current has increased sufficiently to produce the required new torque. But remember that a small change in back emf results in a large change in armature current —if the line voltage is 120 and the original back emf is 110, the armature current might be 5 amperes (as explained on page 100); if the speed and hence the back emf drop only 10%, to a new back emf of 100 volts, the current will *double*. Hence a change of speed of only 10% has increased the torque by 100%. The shunt motor is thus seen to have good speed regulation—it adjusts to any torque requirements by relatively small changes in speed. For this reason the shunt motor is suitable for driving machines which must run at constant speed and where the load varies widely from almost nothing to a maximum.

The series motor. In the series motor, the field winding is in series with the armature. The immediate result of this is that the field strength varies with the armature current. At slow speeds (or when starting from rest) the back emf is small and the armature current of the motor is large. The field strength is also large. As a result, the starting torque of the series motor is very great, making it suitable for motors which have to start against heavy torques (street car and subway motors, for example). However, the speed regulation of the series motor is poor. In fact, if the load is removed from a series motor, it "runs away"—continues to increase in speed until it destroys itself. Thus series motors must be connected permanently to their loads, and the load must never be permitted to fall too low.

Series motors are suitable for such applications as fans, where there is a resistance to turning at any speed, and where any increase in speed would meet an increase in torque—thus preventing "running away."



The Shunt Motor **The Series Motor**

The large black dots represent the terminals of the motor, where connection to the power line is made. The field connections are usually made inside the motor.

Starting Boxes. It has been mentioned that the starting current of a DC motor is very high because there is no back emf at zero speed. To prevent damage to the armature which would result from large currents at starting, a resistance is placed in series with the armature before connecting the motor to the line voltage. This resistance limits the current to a safe value. As the motor starts up, back emf builds up and reduces the armature current; the resistance is then removed, and the motor allowed to run connected directly to the line. It is usually necessary to cut out the resistance in steps, since each reduction in resistance is accompanied by a fresh surge of current and a fresh increase in speed; if the resistance were cut out all at once, the current surge would be almost as bad as though no starting resistance had been used to begin with. Such starting resistances, with a switch for cutting out resistance as the speed builds up, are grouped in a *starting box* for the motor. The motorman's control handle on a street car is actually the control lever of such a starting box.

AC Motors. The *series* motor will operate on AC almost as well as on DC. Note that even though the current through the armature coils is repeatedly changing direction, so is the current through the field coils. Consequently, the polarity of the magnetic field always reverses in step with the reverses of the armature current—and as a result the turning force on the armature is always in the same direction. AC-DC motors, such as those used in fans, some electric razors, and similar applications, are usually series motors.

The *shunt* motor will not operate very well on AC. Although the field polarity changes direction periodically as in the series motor, the changes do not keep in step with those in the armature, because the inductances of armature and field coils are unequal. Since the two paths for the current are in parallel, the armature current and field current are "out of phase" (see Chapter 9).

The *induction motor* is purely an AC motor—it will not work on DC. The field of this motor is similar to that of DC motors, but the armature coils are not connected to any outside circuit; they are short-circuited within the motor. When AC voltage is applied to the field coils, large currents are induced in the armature coils by transformer action. These currents then react with the magnetic field and rotate the armature just as though the armature current were being supplied from an external circuit. Of course, no transformer action will occur on DC, and the motor will not function.

BEST ANSWER TEST

1. A current will be induced in a conductor whenever it is made to (*a*) move parallel to lines of force; (*b*) cut lines of force; (*c*) come in contact with a magnet.

2. Electrical energy is transformed into mechanical energy by means of (*a*) the dynamo; (*b*) the motor; (*c*) the transformer; (*d*) the magnet.

3. A series motor (*a*) has the armature and field connected in parallel; (*b*) runs at nearly constant speeds at all loads; (*c*) might be used to drive an electric truck; (*d*) has a small initial torque.

4. The purpose of the commutator in the electric motor is to (*a*) cause a magnetic field; (*b*) reduce the resistance of the armature; (*c*) reverse the current in the armature; (*d*) increase the resistance of the armature.

5. The armature of an electric motor draws less current when running than when held stationary. This is an example of (*a*) the right-hand rule; (*b*) the law of attraction and repulsion, (*c*) Lenz's law; (*d*) transformer action.

6. The effective emf that drives current through a motor is (*a*) the difference between; (*b*) the sum of; (*c*) the product of, the impressed and the counter emf's.

7. The generated voltage of an electric generator is most easily controlled by (*a*) changing the resistance of the armature circuit; (*b*) changing the resistance of the field circuit; (*c*) changing the resistance of the load circuit; (*d*) changing the number of brushes.

8. The essential difference between an AC and a DC generator is (*a*) direction of rotation; (*b*) number of field poles; (*c*) function of the brushes; (*d*) presence or absence of a commutator.

9. When a DC motor is run as a generator, (*a*) it must be rotated in the opposite direction; (*b*) it must have a separate field current supply; (*c*) it converts mechanical energy into electrical energy; (*d*) it can never generate as much voltage as it requires as a motor.

QUESTIONS

1. (*a*) Describe an experiment to show how an electric current may be produced by induction. (*b*) What did the experiment show about the direction of the induced current?

2. What may be done to reverse the direction of rotation of an electric motor? Will reversing the plug in the socket reverse the direction of rotation? Why?

3. Explain how the increased current taken from a generator will automatically cause the driver of the generator to work harder. (Apply Lenz's law or the principle of the motor.)

4. Explain why the high-voltage generators driven by slow-speed water wheels may have as many as 12 pairs of field poles.

5. Compare the field windings of series and shunt motors as to number of turns, size of wire, voltage drop under full load conditions, and size of current under full load. Give reasons for all differences.

6. Explain the need and use of starting boxes for motors. Could the same result be achieved by inserting resistance in the field circuit?

PROBLEMS

1. An electric motor is connected to a 120-volt line. It develops a back emf of 110 volts. The current through the motor when running is 8 amperes. (*a*) What is the net emf driving current through the motor? (*b*) What is the resistance of the motor? Ans. (a) 10 v (b) 1.25 ohms

2. What current will flow through the armature of a motor having a resistance of 7.5 ohms when the impressed emf is 115 volts and the counter emf is 112 volts? Ans. 0.4 amp

3. When the armature of a motor is held stationary and is connected to a 6-volt source, a current of 3 amperes flows. When connected to a 120-volt source and running, the current is 2 amperes. Calculate: (*a*) the resistance of the motor, (*b*) the back emf when running.

Ans. (a) 2 ohms (b) 116 v

EIGHT— MUTUAL AND SELF INDUCTION

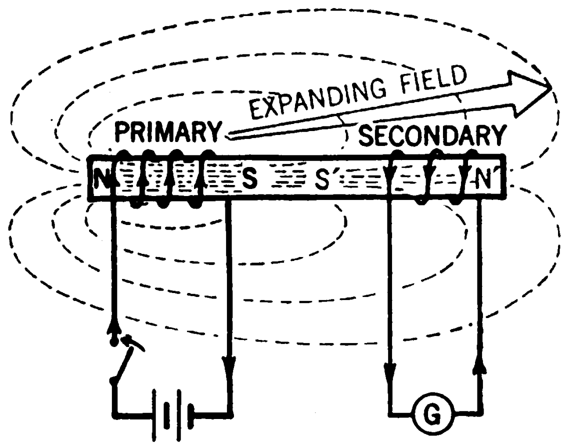
CURRENTS INDUCE CURRENTS

We have seen that when a current flows through a conductor a magnetic field is produced about the conductor in proportion to the intensity of the current. This discovery of Oersted (that an electric current induces a magnetic field) has been applied in the electric bell, the telegraph, the electric motor and other electromagnetic devices.

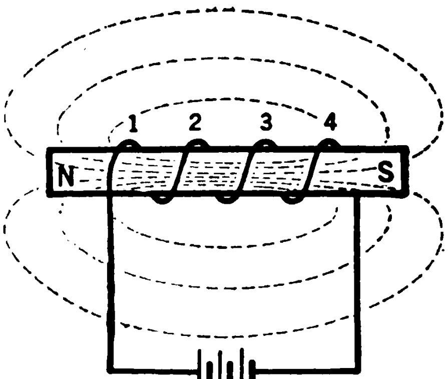
We have also seen that when a coil is moved through a magnetic field, or the field is moved through a coil, an emf is induced in the coil. The magnitude of this induced current depends upon the rate at which the magnetic lines of force are cut. Magnetically induced currents find their chief application in the alternating and direct current generators.

Changing the Magnetic Field Electrically. It will be noted that in the first instance electrical energy was converted into mechanical energy (the electric motor, for example); in the second instance, mechanical energy was converted into electrical energy (the generator, for example). We shall now see how electrical energy with one amperage-voltage ratio can be converted or transformed into electrical energy of a different amperage-voltage ratio. Faraday is credited with this discovery. Instead of moving a magnetic field past a coil by *mechanical* means, he did so by *electrical* means. Applying Oersted's discovery that the strength of a magnetic field about a current-bearing conductor varies with the intensity of the current, he changed (moved) the magnetic field by deliberately varying the intensity of the current. This is shown by his experiment. He wound two independent coils of wire on the same iron core. One coil (the *primary*) was connected to a battery and the other coil (the *secondary*) was connected to a galvanometer. An emf was induced and current flowed in the secondary whenever a current was *started or stopped in the primary.* The *changing* magnetic field produced electrically by the starting or stopping of current in the primary acted exactly like the changing magnetic field produced mechanically by moving a coil and a magnetic field with respect to each other. Thus an emf was induced in the secondary coil. This induced emf is produced whenever the current in the primary is *changing in magnitude or direction.*

Inductance. It will readily be seen from Faraday's experiment above that if only one coil is considered, a changing current in the coil will induce an emf in turns of wire of *the same coil.* According to Lenz's law, this induced emf opposes the change in current producing it. The property of a circuit which opposes any change in the amount of current flowing is called *inductance.* A *coil* of wire in an electrical circuit gives that circuit the property of inductance. Inductance in a circuit is analagous to inertia in



INDUCTION



SELF-INDUCTION

In the diagram at the left, as the switch is closed, current builds up in the primary. This increasing current produces an expanding magnetic field which "sweeps" across the turns of the secondary, inducing a current in the secondary. Note that the magnetic field of the induced current is opposite in polarity to that of the primary.

The diagram at the right illustrates how induction takes place within a single coil. Let us assume the diagram shows the current and magnetic field at maximum strength. If the circuit is now broken, the field will collapse. As the collapsing field sweeps across the individual turns of the coil, an emf is induced which opposes the change in current producing it. Thus the induced emf tends to keep the current flowing even after the circuit is broken. This induced emf is often sufficient to cause a spark to jump the gap in the circuit.

in mechanics; in fact, inductance is sometimes called *electromagnetic inertia.*

When current begins to flow in a coil, the resulting magnetic field builds up and sweeps through the coil, inducing a back emf in the coil which tends to prevent the rise in current. Hence, the current builds up slowly to maximum strength. When the current flow is steady and there is no relative motion of magnetic field and conductor, no inductance effect is produced. When the current is stopped, the magnetic field collapses or withdraws, and the induced emf is in the opposite direction; that is, it tends to oppose the stopping of the current and to keep it flowing. With alternating current, these effects of inductance are produced with every alternation of the current and have a very important influence over the current which flows.

Mutual inductance is the term used when the effect of induction is such that a current change in one circuit produces an induced emf in another circuit. The term "magnetic coupling" is often used to indicate that there is a mutual inductance between two coils. A common application of mutual inductance is in the transformer.

The magnitude of inductance depends upon the physical characteristics of the coils, such as size, number of turns, spacing between turns, etc.

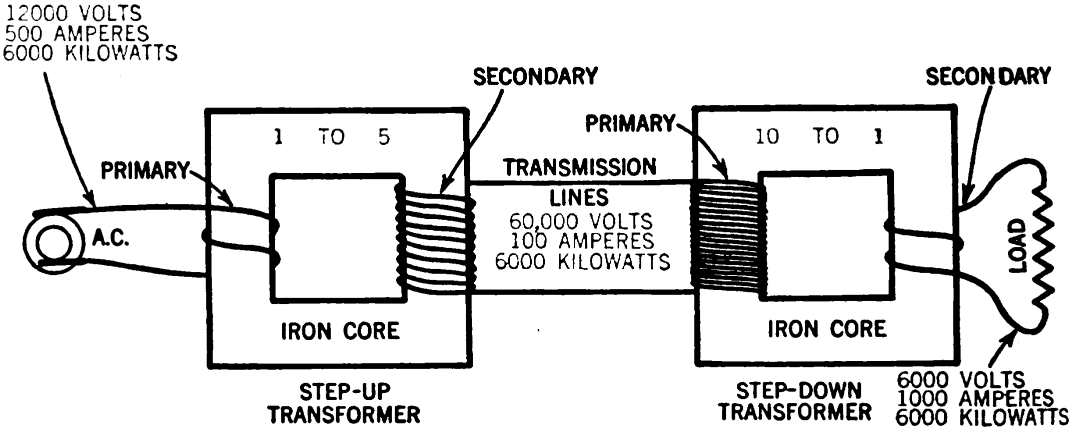
The *henry* is the unit of inductance. It may be defined as *the inductance present when a current change of one ampere per second produces an induced emf of one volt.* The symbol for inductance is L. Practical units of inductance, except for large iron-cored coils, are the *millihenry* and the *microhenry* (for radio coils, for example).

The Transformer. The transformer is used to control the voltage of an alternating current. This electrical device consists essentially of a primary coil and a secondary coil insulated from each other, but wound on the same iron core and thus coupled together by mutual inductance. When alternating current flows in the primary, an alternating magnetic field is established through the iron core. The lines of force in the core cut the windings of the secondary coil and induce an alternating emf in this circuit. The voltage of the primary bears the same ratio to the voltage induced in the secondary that the number of turns in the primary coil bears to the number of turns in the secondary coil.

$$\frac{\text{Primary Voltage}}{\text{Secondary Voltage}} = \frac{\text{Primary Turns}}{\text{Secondary Turns}}$$

$$\frac{E_1}{E_2} = \frac{N_1}{N_2}$$

A *step-up* transformer is one in which the output voltage is greater than the input voltage; that is, the secondary has more turns than the primary. Transformers of this type are used in the commercial transmission of electric power over long distances and in the operation of X-ray tubes, neon signs, fluorescent lights, and numerous electrical devices; small step-up transformers are frequently employed in certain radio circuits.



A *step-down* transformer is one in which the output voltage is less than the input voltage; hence, the secondary has fewer turns than the primary. Bell-ringing transformers are of this type; step-down transformers are also used in electric welding and to reduce the voltage of commercial electric power to suitable and safe values for use in homes and for other applications.

Power Transmission in the Transformer. The transformer does not create electrical energy; it merely changes the voltage-amperage ratio in the same way that a mechanical machine changes the force-distance ratio. As with machines, if the transformer were 100% efficient, the power output (secondary volts × secondary amperes) would equal the power input (primary volts × primary amperes).

$$E_1I_1 = E_2I_2, \text{ or } \frac{E_1}{E_2} = \frac{I_2}{I_1}$$

However, there are some energy losses in the transformer, but they are small compared to the losses in mechanical machines. Transformers having efficiencies from 95% to more than 99% are not unusual. Again, as in the case of machines,

$$\text{Efficiency} = \frac{\text{Power Output}}{\text{Power Input}}$$

One reason for the more widespread use of AC power than of DC power is the ease with which the voltage can be increased for long-distance transmission and then reduced for local consumption. Stepping up the voltage reduces the current and enables a given amount of power to be transmitted through smaller wires and with smaller heat losses. Why this is so becomes clear when it is recalled that (1) the flow of current through a conductor always produces heat; (2) the amount of heat produced is proportional to I^2R. Hence, the energy loss along the line is only ¼ as much when 1 ampere flows as when 2 amperes flow, or ⅑ as much as when 3 amperes flow, etc.

Alternating current is just as well suited for lighting and heating purposes as direct current and motors have been devised which operate well on AC. However, AC cannot be used for electroplating, electrolysis, charging storage batteries, and similar purposes, but this disadvantage can be overcome by changing the AC to DC by the use of rectifiers (p. 129), or by using an AC motor to drive a DC generator.

TYPICAL PROBLEMS

A transformer has 600 turns of wire in the primary coil and 20 turns in the secondary coil. The input voltage is 3600 volts. What is the output voltage?

$$\frac{E_1}{E_2} = \frac{N_1}{N_2}$$

$$\frac{3600}{E_2} = \frac{600}{20}$$

$$E_2 = \frac{3600 \times 20}{600} = 120 \text{ volts}$$

If a current of 3 amperes is drawn from the secondary of the above transformer, and 98% efficiency is assumed, (*a*) what is the

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power output; (*b*) what is the power input; (*c*) what current flows in the primary?

(*a*) Power Output = Secondary Volts × Amperes

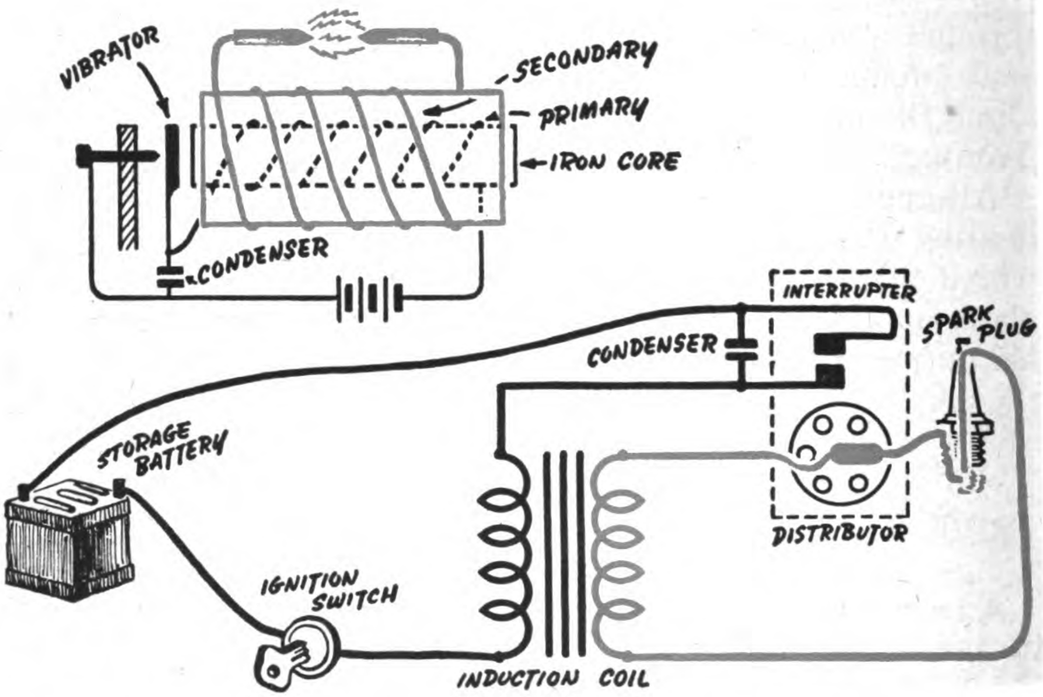
$$W_2 = E_2 \times I_2;\ W_2 = 120 \times 3 = \mathbf{360\ watts}$$

(*b*) Power Input × Efficiency = Power Output

$$W_1 \times 0.98 = W_2;\ W_1 = \frac{W_2}{0.98} = \frac{360}{0.98} = \mathbf{367\ watts}$$

(*c*) Power Input = Primary Volts × Amperes

$$W_1 = E_1 \times I_1;\ I_1 = \frac{W_1}{E_1};\ I_1 = \frac{367}{3600} = \mathbf{0.102\ amp}$$



The Induction Coil. The lower diagram shows the application of the induction coil to the ignition system of an automobile. In both diagrams the secondary circuit is shown in red.

The Induction Coil. The induction coil is substantially a transformer that operates on direct current. The essential parts of the induction coil are: (1) a *primary coil* of fairly heavy wire wound upon (2) a soft iron *core;* (3) an *automatic make and break* device (vibrator) as in the electric bell; (4) a *secondary coil* of

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very many turns of fine wire wound around the primary and completely insulated from it, the open ends of the secondary coil forming a spark gap; (5) a *condenser* connected in parallel with the vibrator to absorb current surges and thus prevent excessive sparking at the contact points of the primary circuit.

With each "make" and "break" of the primary circuit, a magnetic field builds up about the primary and then collapses, cutting the many more turns of the secondary. Since the "break" occurs much more quickly than the "make" and the magnitude of the induced emf depends on the rate of change of current, a spark is produced between the terminals of the secondary only on the "break." Hence the output of the induction coil is a rapidly pulsating DC. Although the secondary voltage is very high, the current in the secondary is very small, since the power output (secondary volts × amperes) cannot be larger than the power input (primary volts × amperes).

Induction coils provide the high voltage needed to produce sparks at the spark plugs of automotive and aircraft engines.

The Automobile Ignition System. The diagram on the preceding page illustrates the main elements of an automobile ignition system.

1. *Source of electrical energy.* The main source of current is the storage battery, which generates about 6 volts. When the ignition switch is turned on, the battery circuit is closed. The car radio, heater, horn, lights, and other electrical devices draw current from the battery. Self-starter motors are also operated by the battery. As the engine is started, the battery supplies the current for the primary circuit in the spark plug ignition system. Once the motor is running, the mechanical energy produced by the exploding fuel in the cylinders rotates a generator which recharges the battery and at the same time supplies electrical energy to the ignition system.

2. *Induction coil.* As explained above, the induction coil steps up the voltage of the battery or generator and, via the secondary circuit of the coil, delivers electric energy to the spark plugs.

3. *Timer-distributor.* The timer, or interrupter, is a circuit breaker inserted in the primary circuit. It is operated by an eccentric cam connected to the engine. As the cam rotates it makes or breaks the circuit and this produces a sparking voltage at fixed time intervals. The distributor contains a rotating switch which

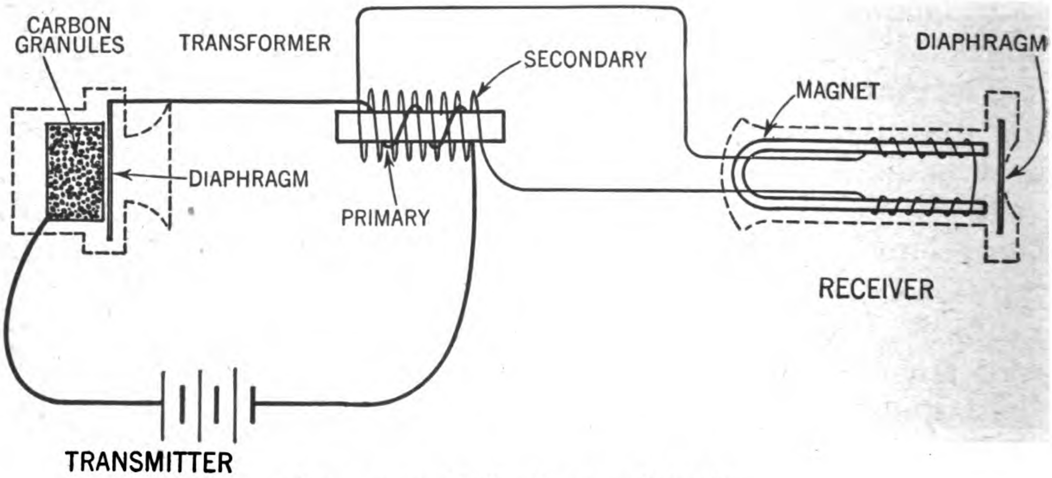
distributes the current from the secondary circuit to the proper cylinder and thus provides the spark to the right cylinder at the right time.

4. *Spark plug.* The spark plug, connected to the secondary circuit, provides the spark which explodes the fuel in the cylinder.

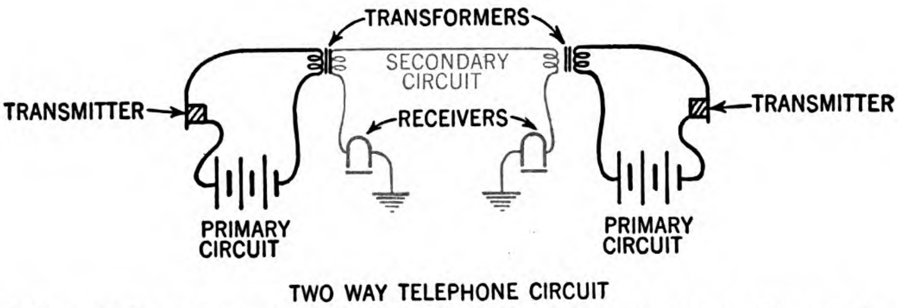
Principle of the Telephone. The essential parts of a telephone system are transmitters, receivers, transformers, a source of electric current, and a line to carry the current from one station to another.

The transmitter is really a box filled with carbon granules and a movable diaphragm as one side of the box. The receiver consists of a permanent magnet around each pole of which is wound a coil of wire. The receiver also contains a thin iron diaphragm.

Sound waves enter the transmitter and cause its diaphragm to vibrate. This motion of the diaphragm compresses and releases



One-way Telephone Circuit



Two-Way Telephone Circuit. The secondary circuit is shown in red. Either transmitter will actuate both receivers.

the carbon granules, changing their electrical resistance. When the carbon granules are compressed, they are in good contact and offer less resistance to the flow of current than when they are released and make poor contacts with each other. The current through the transmitter circuit, therefore, fluctuates in step with the sound waves that set the diaphragm in motion.

By transformer action, this fluctuating current induces a much higher emf with corresponding fluctuations in the receiver circuit. The fluctuating current which flows to the receiver varies the strength of the magnet which attracts the thin iron diaphragm. This causes it to vibrate at the same rate and in the same manner as the diaphragm of the transmitter, and thus to reproduce the sounds impressed upon the transmitter.

BEST ANSWER TEST

1. In a step-down transformer the current in the secondary is (*a*) the same as, (*b*) smaller than, (*c*) larger than that in the primary.

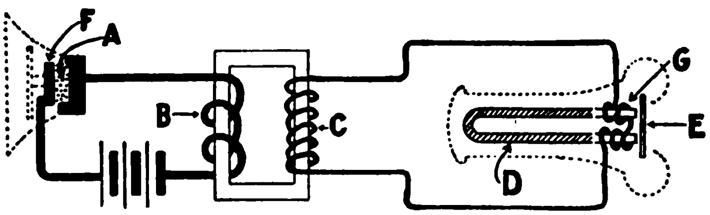
2. The diaphragm of the receiver of a telephone must be made of (*a*) copper, (*b*) hard rubber, (*c*) iron, (*d*) tin.

3. A telephone transmitter contains (*a*) an electromagnet, (*b*) a transformer, (*c*) a permanent magnet, (*d*) carbon granules.

4. Because of inductance, the current flowing in a coil of wire (*a*) never stops flowing, (*b*) does not produce a magnetic field, (*c*) flows only halfway through the coil, (*d*) seems to have the property of inertia.

5. The *henry* is (*a*) the unit of capacitance, (*b*) the unit of inductance; (*c*) 1 ampere per second, (*d*) 1000 microhenries, (*e*) the core of an electromagnet.

6. Referring to the diagram of the telephone system, complete the following statements:



(*a*) The part marked A is usually made of ________.

(*b*) The part marked F is called the ________.

(*c*) The part marked B is called the ________.

(*d*) The part marked C is called the ________.

(*e*) The part marked D is usually made of ________.

(*f*) The part marked E is usually made of ________.

(*g*) When the transmitter is in use, the current in B is ________ (steady direct, alternating, pulsating direct).

(*h*) The current in C is ________ (steady direct, alternating, pulsating direct).

(*i*) The voltage of the current in C is ______ (lower than, higher than, the same as) the voltage of the current in B.

(*j*) It is the variation of the ______ (current, resistance, temperature) in G that causes E to move.

7. A bell transformer delivers 6 volts and is supplied with 120 volts. If the primary has 1000 turns, the secondary has ______ turns.

8. The induction coil produces a spark that has extensive use in ____.

9. A current is induced in the secondary of an induction coil when the primary current is ______.

10. When the carbon granules in the telephone transmitter are compressed, the resistance is ______ and the current is ______.

QUESTIONS AND PROBLEMS

1. Give two reasons why it is more economical for electric companies to furnish their patrons with alternating current rather than with direct current.

2. The voltage of alternating current is often raised to 22,000 volts or more, in order that the current may be transmitted long distances economically. Describe how this change in voltage is accomplished and explain why economy results.

3. A toy electric motor is made to operate on a 10-volt alternating current. Houses are usually supplied with a 110-volt alternating current. (*a*) Given a supply of insulated wire and an iron rod about 1 in in diameter and 8 in long, explain how to obtain a suitable current to operate the toy motor. (*b*) Make use of a diagram to show the proper electric connections and indicate, wherever coils are used, the approximate number of turns of wire in each coil. (*c*) Explain why a commercial device made for this purpose would probably be more efficient.

4. State whether each of the following statements is true or false and give reasons for your answer.

(*a*) A transformer will operate either on AC or on pulsating DC.

(*b*) A bell-ringing transformer is a step-down transformer.

5. Explain how the voice causes a variable current to flow in the telephone circuit.

6. State the main elements in an automobile ignition system and describe the function of each element.

7. The primary of a transformer has 300 turns and carries a current of 2 amperes when connected to a 110-volt line. The secondary has 1500 turns. Assuming 100% efficiency, calculate (*a*) the output voltage, (*b*) the current in the secondary. Ans. (a) 550 v (b) 0.4 amp

8. A transformer has 1600 turns in the primary and 200 turns in the secondary. It is connected to a 120-volt line and 0.4 amp is drawn from the secondary. Assuming 96% efficiency, calculate: (*a*) output voltage; (*b*) output power, (*c*) input power, (*d*) input current.
Ans. (a) 15 v (b) 6 watts (c) 6.25 watts (d) 0.052 amp

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NINE— ALTERNATING CURRENT

General. *A direct current is one that always flows in the same direction.* However, even a direct current must start from zero and build up to a steady value when a switch is closed. Ordinarily, these momentary variations may be neglected.

An alternating current is one which continually changes in magnitude and periodically reverses in direction. That is, the current builds up from zero to a peak value in one direction through the conductor, then dies down to zero; builds up to a peak value in the opposite direction, then dies down to zero—and so on, repeatedly. Thus the momentary variations produced in DC circuits by opening and closing a switch are ever-present in AC circuits.

Since the flow of current produces a magnetic field, an alternating current produces a field which repeatedly expands and collapses, reversing polarity with each reversal of direction of the current. If this field cuts a conductor, a voltage is induced in it. The induced voltage may act on the circuit itself (self induction), or on any other circuit with which it is coupled (mutual induction).

In order to take into account the induced voltages which are nearly always present in AC circuits, in addition to the impressed voltage, special AC formulas for Ohm's law have been developed.

Generation of AC Voltage. The nature of alternating current can readily be understood by the study of a model AC generator and its action plotted in graph form. Connect the generator to a galvanometer and rotate the coil slowly at uniform speed in a counter-clockwise direction. (See diagram, page 118.)

When the coil moves through the horizontal position (0°) shown in the illustration, the initial induced emf will be zero because the sides of the loop, AA′ and BB′, move parallel to the lines of force in the field, and therefore do not cut any (A on the central diagram). The fact that all of the lines of force pass through the

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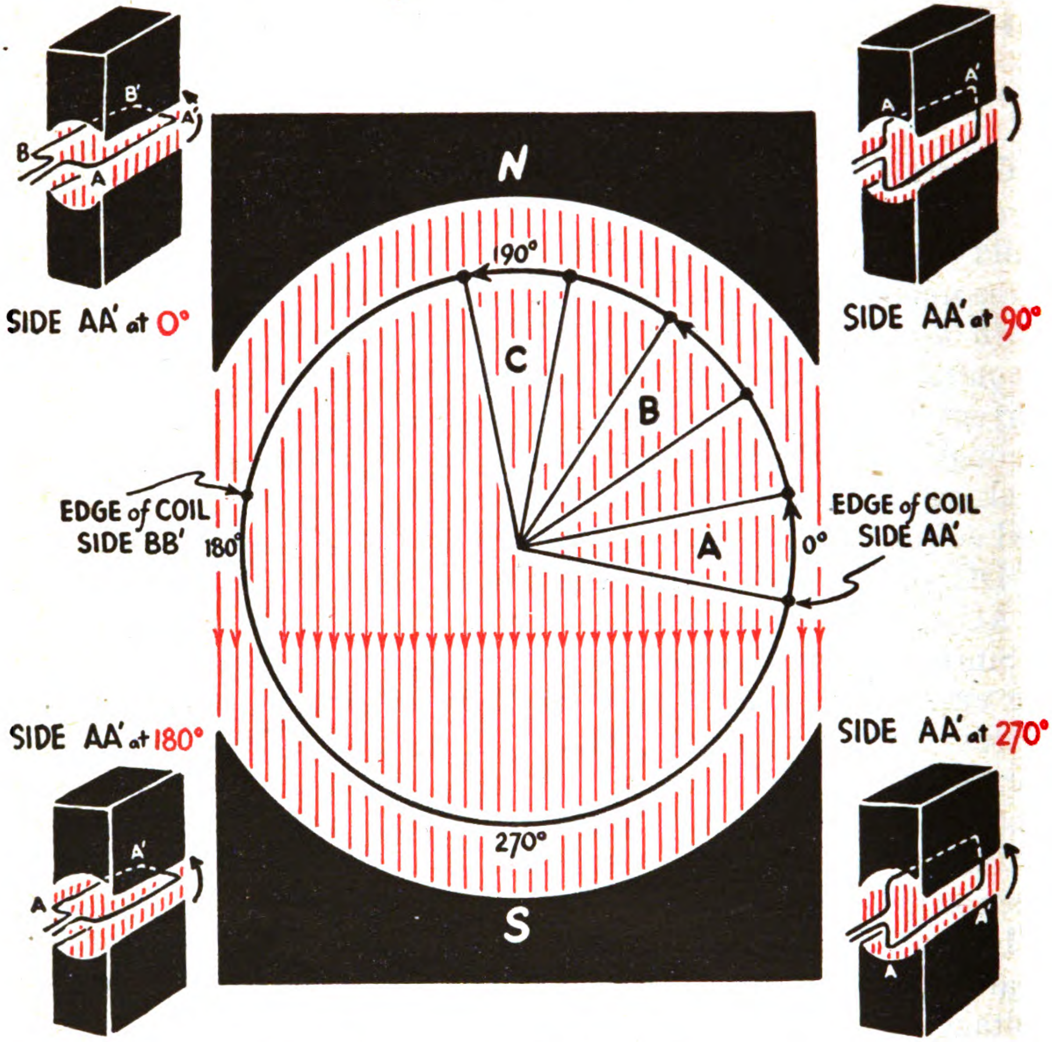
coil when it is at this position does not mean that there is an induced emf. The magnitude of the induced emf is proportional to the *rate* at which lines of force are cut.



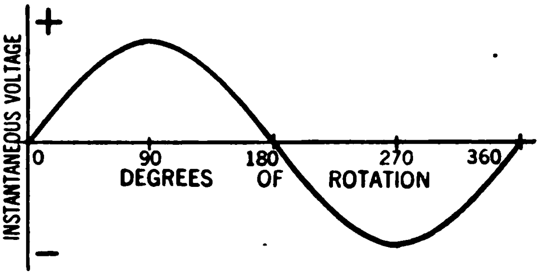
Generation of AC Voltage. The four small diagrams show the coil in four positions.

As the coil rotates away from the horizontal position, very little emf is induced at first because, during a small angular movement, comparatively few lines of force cut the coil. As rotation continues (B and C), the coil cuts the lines of force at an increasing rate and the induced emf increases accordingly. In B, for example, the coil cuts 5 lines of force. In C it cuts 7 lines. Maximum emf is induced when the coil reaches the vertical position (90°), because then AA′ and BB′ move at right angles to the field and, during a small angular movement, the maximum number of lines of force are cut.

As rotation of the coil continues, the induced emf has the same direction (Fleming's right-hand rule, page 290), but gradually diminishes until it again becomes zero when the coil reaches the horizontal position (180°). Beyond this point the direction of the induced emf reverses. AA′ is now moving down and BB′ is moving up. The magnitude of the voltage again increases to a maximum when the coil has rotated 270°, and then gradually decreases to zero as the coil once more reaches the horizontal position from which it started.

One complete rotation of the coil takes 360° and is called a *cycle*. There are two *alternations* or reversals in every cycle. The number of cycles per second is the *frequency*. The voltage being generated at any instant is called the *instantaneous* voltage, and is represented by the small letter, *e*.

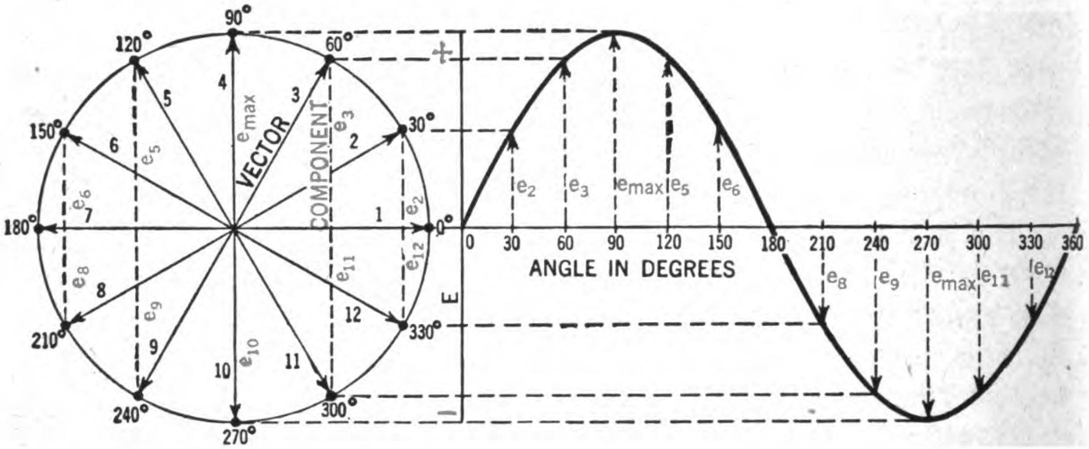
Graphic Representation of AC Voltage or Current. If the magnitude of the induced voltage at any instant is plotted against the number of degrees through which the coil has rotated from the initial position, the graph obtained is a *sine curve;* that is, it has the same form as the curve obtained by plotting the sine of an angle against its measurement in degrees. The current produced by an alternating emf also has a sine wave form.



Sine Curve of AC Voltage

Interpretation of a Rotating Vector in Graph Form. A *voltage vector* is a straight line drawn to scale to represent the *maximum voltage* (E_{max}) produced by the generator. By imagining that the vector rotates counter-clockwise about a point, the *instantaneous voltage* at any angular position of the coil is equal to *the vertical component* of the rotating vector at that position, or *phase*.

In the illustration (page 120), the arrow shown at position 1 represents the voltage vector at its 0° position. At this position, the vector has no vertical component; hence, the emf is zero. 30° of rotation brings the vector to position 2, and the instantaneous emf (e_2) at this point is represented by the scale value of the vertical component. At 60° of rotation, component e_3 is the instantaneous voltage. When the rotating vector reaches the 90° position, the vector and its vertical component are equal; this means that the instantaneous voltage is maximum (E_{max}).



When this interpretation is continued for 360° of rotation and all the instantaneous voltage values are plotted, the simple sine curve shown in the illustration is obtained.

Measurement of an Alternating Current. Since the strength (amperage) of an alternating current changes from instant to instant, the question arises as to how to measure the effective strength of the current in amperes. The best method is to find the DC current value which produces the *same heating effect* (that is develops the *same power*) as the AC current in question. This current value is called the *effective* value (I_{eff}) of the AC current and is found to be 0.707 times the maximum current:

$$I_{eff} = 0.707\, I_{max}$$

By using the effective value, AC and DC currents can be compared, and voltage, current, and power relationships on AC can be determined as readily as on DC. AC meters read effective values of current and voltage. The effective value of AC voltages is defined in the same way as that of AC currents, and bears the same ratio to the maximum value:

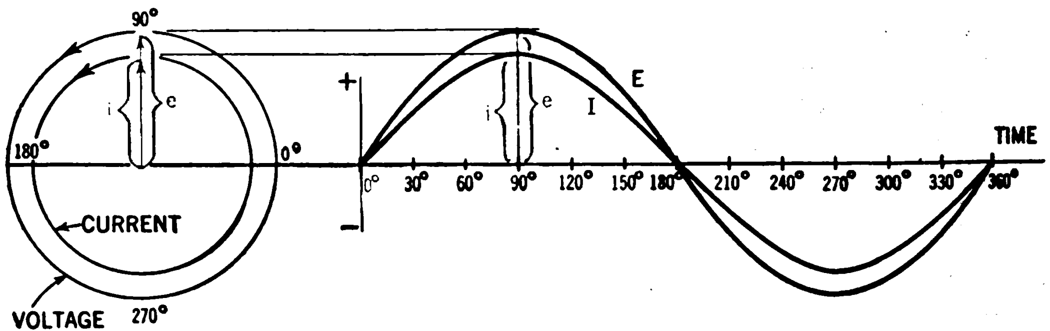
$$E_{eff} = 0.707\, E_{max}$$

Phase Relations of AC Voltage and Current. In AC, voltage and current do not always reach their zero and maximum values at the same instant. If the zero and maximum points on the sine curves of voltage and current in an AC circuit coincide, the voltage and current are said to be *in phase.* This means that they vary in step with each other; both pass through zero and reach their peak values at exactly the same time. If they do not vary in step with each other, that is, if one passes through zero or reaches its peak value at a different time from the other, they are said to be *out of phase.* Whichever passes through zero or reaches its maximum value first along the time axis is said to *lead* the other.

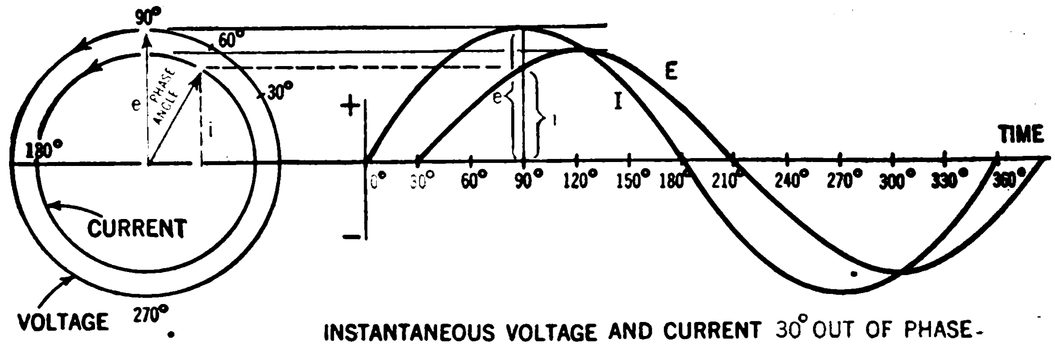
The graphic representation of a rotating vector will illustrate phase relationships between alternating current and voltage. In the top diagram, voltage and current are in phase, as shown by the sine curve representation of the rotating vectors. (The horizontal axis is marked off in degrees corresponding to the positions of the voltage vector and represents the time interval for one cycle.) The outer circle represents the circumference described by the rotating voltage vector. In the position shown, the voltage vector is at 90°; therefore its vertical component or instantaneous voltage is maximum. The inner circle represents the circumference described by the rotating current vector, which is also at maximum. Since both voltage and current are at maximum value (90°) *at the same instant,* they are said to be in phase.

In the diagram (p. 122), the voltage and current vectors are shown at the instant that the voltage vector reaches 90°. At this instant the current vector is, let us say, at 60°. In other words, the voltage and current are out of phase. The angle between the two vectors indicates the extent to which they are out of phase. This angle is called the *phase angle.* The phase angle in this case is 30°. Since the current vector is 30° behind the voltage vector, the current is said to *lag* the voltage by 30° (or voltage *leads* current by 30°). This phase angle remains constant as these two vectors rotate. The phase angle between voltage and current may be anything between 0° and 180°, lead or lag.

Phase relationships may exist between voltage and current, as above. As will be seen when we consider alternating current circuits containing coils and condensers, phase relationships may also exist between a voltage in one part of a circuit and a voltage in another part, or between a current in one part of a circuit and a current in another part of a circuit.



INSTANTANEOUS VOLTAGE AND CURRENT IN PHASE



INSTANTANEOUS VOLTAGE AND CURRENT 30° OUT OF PHASE

Impedance in AC Circuits. If a DC voltage of 120 volts is applied to a straight conductor whose resistance is 8 ohms, a DC current of 15 amperes will flow ($120 \div 8$). If an AC voltage of 120 volts (effective) is applied to this straight conductor, the AC current produced will also be 15 amperes. Imagine now that this conductor is wound into a coil around an iron core. When the DC voltage of 120 volts is again applied, the current will still be the same—15 amperes—since the resistance of the wire has not changed. However, when 120 volts of AC are applied, the back emf of self-induction (see p. 108), produced by the ever-varying magnetic field of the AC current, opposes the applied voltage, and the current is consequently less than 15 amperes.

This opposition to the flow of AC currents through an inductance, apart from its DC resistance, is called *inductive reactance.* Inductive reactance is measured in ohms, and is represented by X_L.

The total opposition of the coil to the AC current (that is, the combination of its reactance and its resistance) is called impedance, also measured in ohms, and represented by Z. For AC circuits, Z is substituted for R in Ohm's law:

$$Z = \frac{E}{I};\ I = \frac{E}{Z};\ E = IZ$$

Calculation of Inductive Reactance. The amount of reactance offered by a given coil depends on two quantities:

1. The *frequency* of the AC current—as the frequency increases, the rate at which the current is changing also increases, thus increasing the strength of the back emf and hence increasing the reactance. Inductive reactance is proportional to frequency.
2. The *inductance* in henries—the greater the inductance the greater is the back emf produced, and hence the greater is the reactance.

Mathematically, inductive reactance in ohms is given by the following formula:

$$X_L = 2\pi f L$$

where f is the frequency in cycles per second, and L is the inductance in henries.

Calculation of Impedance. The impedance of a coil is, as we have just stated, the combination of resistance and reactance. However, it is not the arithmetical sum of the two. We shall now see how the actual impedance can be determined by using our knowledge of vectors. The vector representation of currents and voltages is an extremely powerful tool—in fact, without it it would be almost impossible to analyze alternating current circuits.

Consider first a pure inductance (one with no resistance) in series with a pure resistance, connected to an AC voltage source. There will be an AC current flowing in this circuit and, since the inductance and resistance are in series, the currents in both must be identical in magnitude and in phase.

When the current is passing through its zero value, it is changing most rapidly. Hence the emf of self-induction across the coil is maximum at this instant. When the current is at its maximum value, it is not changing at all; hence the induced emf must be

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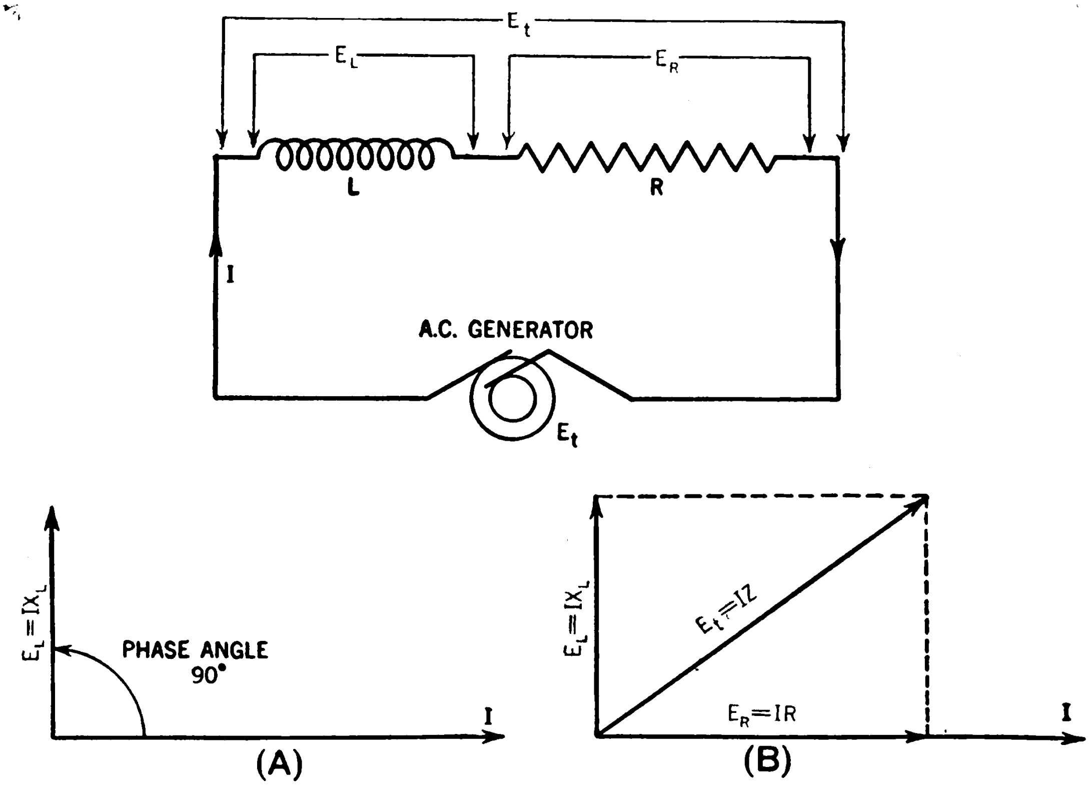

(A) (B)

Inductance and Resistance in Series

zero at that instant. Thus we see that the back emf of an inductance is 90° out of phase with the current—the voltage is maximum when the current is zero and vice versa. In other words the voltage E_L across the coil (which is equal to the back emf) is 90° out of phase with the current. Actually it *leads* the current by 90°. This can be represented by the vector diagram (A) showing E_L as a vector leading I by 90°.

Since the coil is assumed to have no resistance, its impedance is just its reactance, X_L. Therefore we have written $E_L = IX_L$ on the vector (applying Ohm's law for AC).

In the resistance, however, current and voltage are in phase: at the instant of zero current, there is zero voltage drop; at the instant of maximum current, there is maximum voltage drop across the resistance. Thus E_R is shown as a vector in phase with the current I, and equal to IR (vector diagram B).

What, then, is E_t, the total voltage across this circuit? It is the sum of E_L and E_R, but not their arithmetical sum—it is their *vector* sum as found by the method explained on page 177. Thus

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we show E_t as the vector sum of E_L and E_R (diagram B). By Ohm's law, $E_t = IZ$, Z being the actual impedance of the entire circuit.

Applying the Pythagorean theorem,

$$E_t^2 = E_L^2 + E_R^2$$

or, substituting their equivalent values,

$$(IZ)^2 = (IX_L)^2 + (IR)^2$$

From the second equation, we can cancel I, giving the following general formula for the impedance of an inductance and resistance in series:

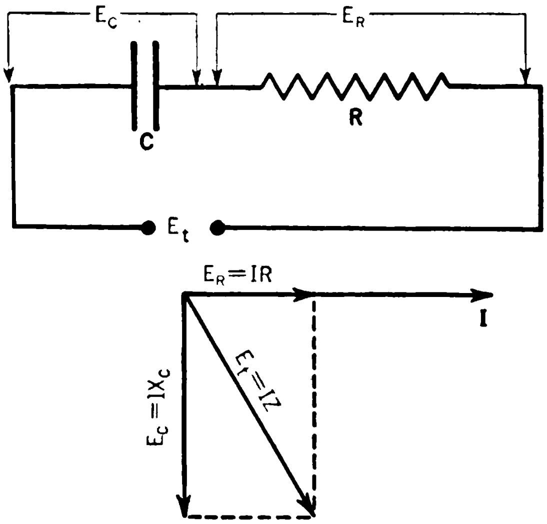
$$Z^2 = X_L^2 + R^2$$

$$Z = \sqrt{X_L^2 + R^2}$$

All practical inductances also have resistance. They act, however, as though they were pure inductances in series with pure resistances, so that the impedance of any coil is given by the same formula.

Condensers and Capacitive Reactance. When a DC voltage is impressed across a condenser in a circuit, there is a small momentary current as the plates of the condenser become charged, after which the current drops to zero. But when an AC voltage is impressed across a condenser, current repeatedly flows into and out of the plates charging them first one way and then the other. Thus, condensers stop or block the flow of DC, but permit the flow of AC.

The voltage across a condenser is maximum and the charging current is zero when the condenser is fully charged. The voltage is zero and the current maximum when the condenser is discharged and about to charge in the opposite direction. Thus, we find that the voltage across a condenser in an AC circuit is out of phase with the current by 90°, as in



Capacitance and Resistance in Series

the case of inductances. However, the condenser voltage *lags* the current by 90°, whereas in the inductance it *leads* by 90°.

Using the same method as for inductances, we can find the impedance of a condenser and resistance in series. The vector diagram is shown in the illustration, with $E_C = IX_C$ lagging $E_R = IR$. The formula for the impedance is:

$$Z = \sqrt{X_C^2 + R^2}$$

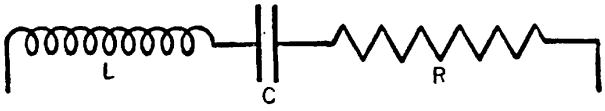
The reactance of a condenser (*capacitive reactance*) varies inversely as the frequency and inversely as its capacitance, C:

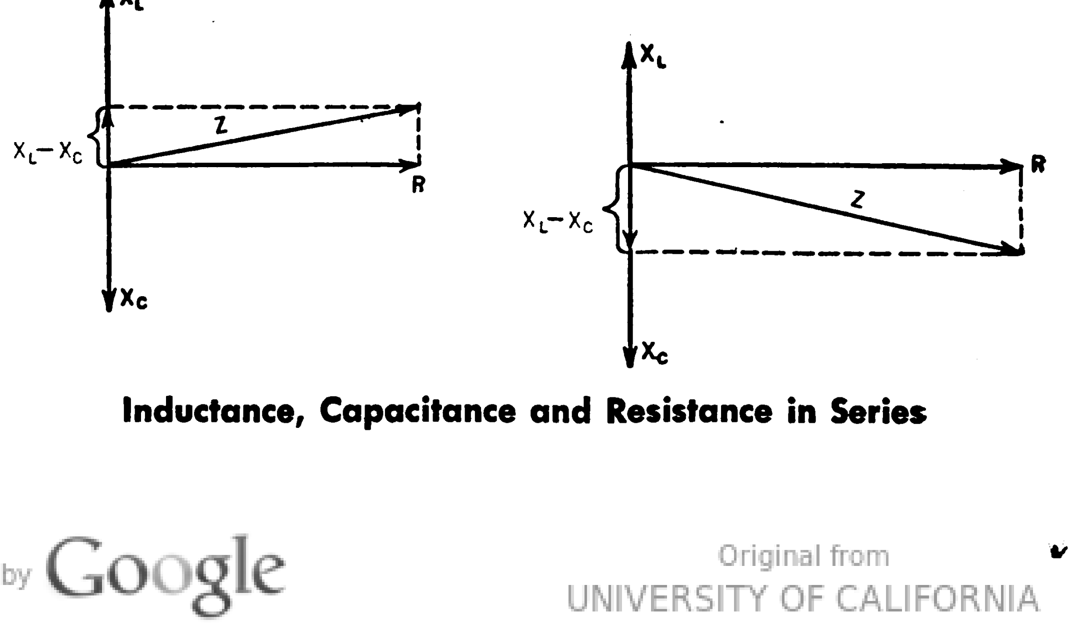
$$X_C = \frac{1}{2\pi f C}$$

Series Circuits Containing Inductance, Capacitance, and Resistance. If the vector diagram of a series circuit containing L, C, and R elements is constructed (see diagram), we find that the total impedance is given by the formula:

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

In other words, capacitive reactance and inductive reactance tend to neutralize each other in a series circuit, because their vectors are in opposite directions. Since X_L increases with an





Inductance, Capacitance and Resistance in Series increase in frequency, while X_C decreases, there is always a particular frequency at which $X_L = X_C$, and the term $(X_L - X_C)^2$ cancels out of the impedance formula. The frequency at which this happens is called the *resonant frequency* of the circuit. At *resonance,* the total impedance consists only of the pure resistance of the circuit. The current is therefore a maximum (for a given voltage), and in phase with the voltage.

We can find the resonant frequency by setting X_L, which is $2\pi fL$, equal to X_C, which is $\frac{1}{2\pi fC}$, and solving for f in terms of L and C. We find that:

$$f_{\text{resonance}} = \frac{1}{2\pi\sqrt{LC}}$$

TYPICAL PROBLEM

A coil of 150 millihenries inductance is in series with a condenser of 2 microfarads capacitance. The coil has a DC resistance of 50 ohms, and the resistance of the condenser is negligible. An AC voltage of 100 volts, 120 cycles per second, is applied to the circuit. (*a*) What is the total impedance of the circuit? (*b*) What current will flow? (*c*) What is the resonant frequency of the circuit? (*d*) What current will flow when the frequency of the applied voltage is the same as the resonant frequency?

(*a*) $Z = \sqrt{R^2 + (X_L - X_C)^2};\ X_L = 2\pi fL;\ X_C = \frac{1}{2\pi fC}$

$$X_L = 2\pi \times 120 \times 0.15 = 113 \text{ ohms}$$

$$X_C = \frac{1}{2\pi \times 120 \times 2 \times 10^{-6}} = 663 \text{ ohms}$$

$$Z = \sqrt{(50)^2 + (113 - 663)^2} = \sqrt{2500 + 302{,}500} = 552 \text{ ohms}$$

(*b*) $I = \frac{E}{Z} = \frac{100}{552} = 0.181$ amperes

(*c*) $f_{\text{res}} = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{0.15 \times 2 \times 10^{-6}}} = 291$ cycles per second

(*d*) $I = \frac{E}{Z} = \frac{E}{R} = \frac{100}{50} = 2$ amperes

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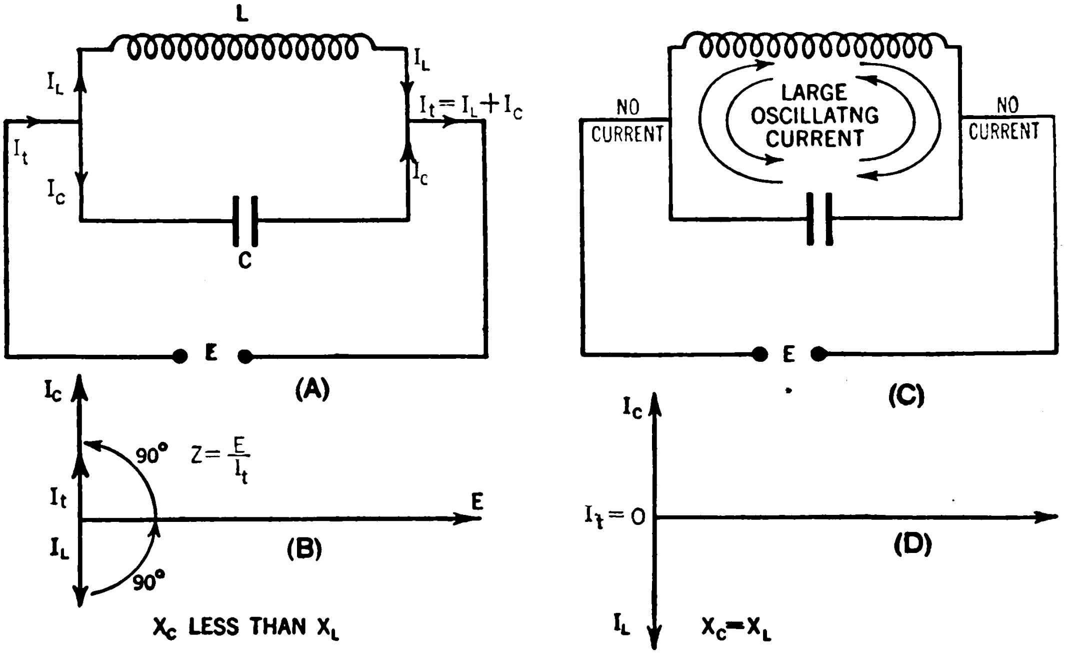
Parallel Circuits and Resonance. When a coil (pure inductance) and a condenser (pure capacitance) are connected in parallel across the same AC voltage (A), an interesting situation occurs. As the vector diagram (B) shows, the current in the inductance (I_L) lags the voltage by 90°, while the current in the condenser (I_C) leads the voltage by 90°. The two currents are therefore 180° out of phase. The total current in the main line, I_t, is the vector sum of the branch currents, I_L and I_C. Since at resonance the inductive reactance equals the capacitive reactance, the two curents I_L and I_C are equal, and their vector sum is zero (D)! In other words, at the resonant frequency (C), no current flows in the main line, ($I_t = 0$). Large currents may, however, be flowing inside the parallel circuit. The use of such parallel resonant circuits in radio is described on pages 151–152.



Resonance in a Parallel Circuit

Actually parallel circuits always contain some resistance. This resistance acts to make the phase angle between the current vectors less than 180°. As a result, even at resonance some current will flow in the main line, but this current is usually very small. Therefore, the impedance of a parallel circuit is always maximum at the resonant frequency. (Compare with a series circuit, in which the impedance is a *minimum* at the resonant frequency.)

Power in AC Circuits. In DC circuits, the product of volts and amperes is the power in watts. In AC circuits this product, called *volt-amperes,* is not always equal to power because voltage and current are often out of phase. If the voltage and current are *in phase* in an AC circuit, the power in watts *is* equal to the product of volts (effective) and amperes (effective):

$$W = E_{eff}I_{eff} \text{ (zero phase angle)}$$

If current and voltage are not in phase (which is usually the case because all circuits contain some inductance or capacitance), the power in watts is given by the following formula:

$$W = EI\cos\phi$$

where ϕ is the phase angle between current and voltage, and E and I are the effective values. Thus if $\phi = 90°$, $\cos \phi = 0$, and there is no power in the circuit. The quantity, $\cos \phi$, is called the *power factor* of the circuit, since it is the factor by which the volt-amperes must be multiplied to obtain true power. The power factor varies from 0 for $\phi = 90°$ to 1 for $\phi = 0°$. For a phase angle of 30°, for example, the power factor (cos 30°) is 0.866.

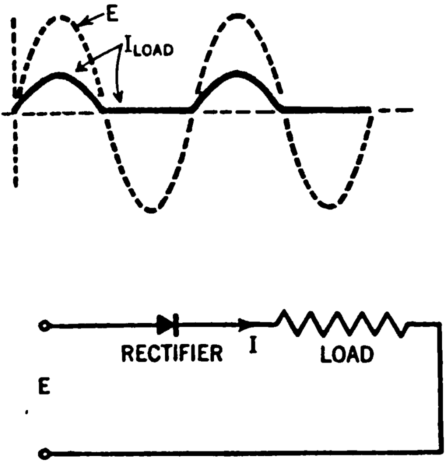
Regardless of phase, power in an AC circuit can always be found by using the formula:

$$W = I^2R$$

Rectification of AC Current. By the use of various devices, some mechanical and some electrical, AC can be changed to DC. The process is called *rectification* and the devices are called *rectifiers.*

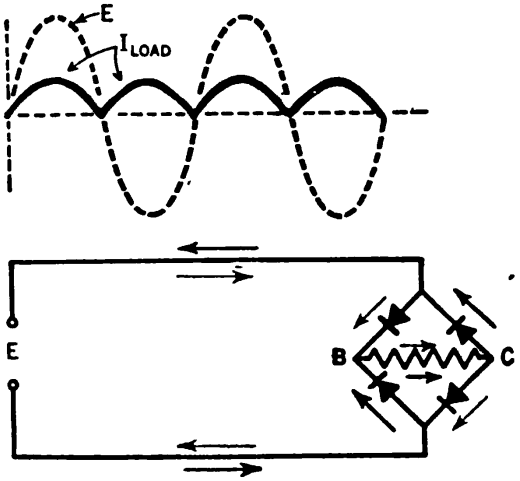
The motor-generator set. This device consists of an AC motor which drives a DC generator. There is no electrical connection between the two machines, but they are mounted on the same shaft. A similar combination may be used to convert DC to AC. The motor and generator are sometimes combined to form one machine called a *rotary converter.*

The copper oxide rectifier. A copper disc coated on one side with red copper oxide offers much less resistance to the flow of current from the copper oxide to the copper than from the copper to the copper oxide. Consequently, an AC voltage gives pulses



HALF WAVE RECTIFICATION

During the half of the AC voltage cycle when the upper terminal is positive, current flows through the rectifier in the direction shown. During the other half of the cycle, no current flows. This is shown in graph form above the circuit diagram.



FULL WAVE RECTIFICATION

The red arrows show the path of the current when the upper terminal is positive. The black arrows show the current flow when the upper terminal is negative. Note that current, in each case, flows through the load in the same direction.

of current in the direction from copper oxide to copper, but there is practically no flow from copper to copper oxide.

A single copper oxide rectifier gives *half-wave* rectification, as shown in the left half of the diagram. Current flows through the circuit only during one half of the voltage cycle. In the diagram at the right, four rectifiers have been connected in a *bridge circuit,* which gives *full-wave* rectification. As the caption explains, current flows through the load resistance during the entire AC cycle, and always in the same direction. Note that the copper oxide rectifier produces a pulsating DC current, not a steady one such as is obtained from DC generators and motor-generator converters.

Copper oxide rectifiers are used in some radios and small battery chargers.

The vacuum tube rectifier. The use of vacuum tubes to rectify AC is explained on page 157.

QUESTIONS

1. (*a*) What is meant by a *sine curve?* (*b*) Explain why it is possible to represent AC voltages and currents by sine curves.
2. How would the wave form of the voltage generated by an alternator be affected if the magnetic field were not uniform?
3. (*a*) What is meant by the *effective value* of an AC voltage or current? (*b*) Why is it desired to use such a value?
4. What is meant by *half-wave* and *full-wave* rectification of AC?
5. Diagram and explain a single diode rectifier.
6. What are some uses for rectifiers of various kinds?

PROBLEMS

1. The maximum voltage generated by an alternator is 160 volts. Calculate: (*a*) the instantaneous voltage at 30° of rotation, (*b*) the instantaneous voltage at 45° of rotation. Ans. (a) 80 v (b) 113 v
2. If the peak value of an AC current is 8 amp, and the voltage peak is 141 volts, what would be the reading of a properly-connected (*a*) ammeter; (*b*) voltmeter? Ans. (a) 5.65 amp (b) 100 v
3. (*a*) What would be the true power in the circuit of problem 2 if E and I are in phase? (*b*) What would be the true power if the phase angle were 60°? Ans. (a) 565 watts (b) 282 watts
4. (*a*) What is the impedance of a circuit containing 300 ohms of resistance and 500 ohms of inductive reactance in series? (*b*) Draw a vector diagram to represent these values. Ans. (a) 583 ohms
5. (*a*) What is the impedance of a circuit containing 500 ohms of resistance in series with 1200 ohms of capacitive reactance? (*b*) Draw a vector diagram to represent these values. Ans. (a) 1300 ohms
6. An AC circuit contains 300 ohms of resistance, 500 ohms of inductive reactance, and 1200 ohms of capacitive reactance in series. (*a*) Calculate the impedance of the circuit. (*b*) Draw a vector diagram to represent these values. Ans. (a) 762 ohms
7. If the line voltage is 120 volts, calculate the current in problem 6. Ans. 0.157 amp
8. With the current flowing as calculated in problem 7, calculate the voltage across each circuit element in problem 6. Ans. R—47.3 v; L—78.8 v; C—189 v
9. A pure inductive reactance of 40 ohms is in parallel with a pure capacitive reactance of 36 ohms, across a voltage of 144 volts. Find (*a*) the current in each branch; (*b*) the line current; (*c*) the impedance of the combination. Ans. (a) $I_L = 3.6$ amp; $I_c = 4.0$ amp (b) 0.4 amp (c) 360 ohms

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TEN— WAVE PHENOMENA AND SOUND

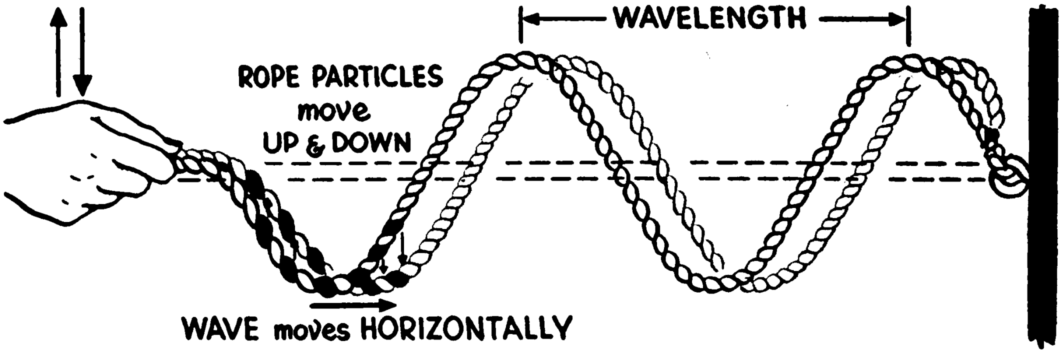
INTRODUCTION

The communication of intelligence is one of the most important elements of modern civilization. The remarkable development in the means of communication has brought the world much closer together than ever before. By virtue of the almost instantaneous and widespread communication between all parts of the earth, the two billion people of the world are first beginning to understand and to appreciate each other's cultures. While it is true that modern, scientific warfare has scourged the earth on an appalling scale, there is hope that fuller understanding among nations and races, brought about by modern communication, will eliminate the hates and misunderstandings that underlie all wars.

In order to understand the most significant of modern means of communication—radio—it is necessary first to understand the principles of wave phenomena and sound.

THE NATURE OF WAVES

Concept of a Wave. If a rope is fastened to a wall, and the free end held in the hand and given a rapid up-and-down motion, a series of bends or crests will be seen to pass along the rope from the hand to the wall. This passage of a series of fluctuations past a point is called a *wave*.



A Transverse Wave. The first position of the rope is shown in black. Its position a moment later is shown in red.

Frequency, Wavelength, and Velocity of a Wave. At any moment, the wave in the rope consists of a series of crests and troughs; a moment later, the crests and troughs have moved along to a new position, but the shape of the wave remains the same. One complete fluctuation is called a *cycle*. The number of crests which pass a given point each second is called the *frequency* of the wave, and is expressed in *cycles per second*. The distance between one crest and the next is the *wavelength*. In every wave:

$$\textbf{frequency} \times \textbf{wave length} = \textbf{velocity}$$
$$fl = v$$

The velocity of a given type of wave depends only on the medium in which the wave is traveling. Increasing the frequency of the wave therefore simply shortens the wavelength. Thus frequency and wavelength are inversely proportional to each other.

Transverse Vibrations in a Wave. In the rope wave, the *form* of the wave moves along the rope, but the rope itself does not move in this direction since both ends are fixed. All that happens is that each small piece of the rope moves up and down as the wave goes by. This can be described by saying that the pieces of the rope vibrate at right angles to the direction of propagation of the wave. Such vibrations are called *transverse*.

A Wave as a Fluctuating Force. Since each piece of the rope moves up and down, it must be acted upon by a force which produces this motion. This force is a fluctuating one which acts upwards half the time and downwards the other half. *If you think of the wave as being just this varying force which travels along the rope,* you will get a partial picture of a radio wave. In a radio wave, nothing moves; but a varying force in space, like the moving force in the rope, travels outward from the transmitter.

Electromagnetic Waves. Radio waves are transverse waves of force in space. This force is partly electrical and partly magnetic in nature; for that reason, radio waves are said to be *electromagnetic*. Radio waves are members of a large group of waves, all of which are electromagnetic, but which differ as to frequency and wavelength. The table on p. 134 lists the different kinds of waves which make up the *electromagnetic spectrum,* and describes the special effects of each. All electromagnetic waves travel through space with the same speed—about 186,000 miles per second.

Energy in Waves. The fluctuating forces propagated as waves

THE ELECTROMAGNETIC SPECTRUM

Wavelength in cm	Name	How Produced	Chief Effects	Uses
Up to .000 000 014	Gamma rays	Atomic disintegration	Penetrate all matter; affect photographic plates; produce phosphorescence; ionize gases; refracted by crystals	Atomic investigations
.000 000 006 to .000 001 360	X-rays	Sudden stoppage of high speed electrons	Same as gamma rays, but less vigorous and penetrating	X-ray photography and fluoroscope
.000 001 360 to .000 040	Ultra-violet rays	Very hot bodies and ionized gases	Affect photographic plates; produce phosphorescence, ionization, chemical effects	Photography, medicine, disinfecting
.000 04 to .000 08	Visible light	Hot bodies and ionized gases	Sensation of vision; photographic and chemical effects	Illumination, photography, signaling
.000 08 to .04	Infra-red rays	Heat radiations from all bodies	Produce heat in bodies; photographic effect on special emulsions	Heat lamps in medicine; special photographic effects
.01 to 1000	Ultra-high-frequency radio waves	Vacuum tube oscillators	Produce currents in conductors; travel in straight lines, can be reflected and focused	Television, FM, radio-location of aircraft
1000 to 3,000,000	Radio waves	Vacuum tube oscillators	Produce currents in conductors; reflected by Kennelly-Heaviside layer in atmosphere	Radio communication
Above 3,000,000	Alternating currents	Coil rotating in magnetic field	Electromagnetic induction	Generators, motors, transformers

carry energy with them. The wave in the rope is a package of energy; in a whip, for example, the energy transmitted to the end of the cord may produce serious cuts on the skin or a loud snap in the air. Ocean waves also carry large amounts of energy.

SOUND

What Is Sound? To be exact, sound is the sensation produced in the brain when the eardrum is caused to vibrate. According to this strict definition, a phonograph playing in a soundproof room produces no sound if there is no ear and brain present to hear it. However, the phonograph does produce sound *waves* in the air of the room, and these waves would produce the sensation of sound in the ears of anyone present. Therefore in practice the sound wave itself is referred to as a sound.

Sources of Sound. All sound originates in matter that is vibrating. A vibrating body forces the particles of air, water, bone, or other medium which surrounds it to vibrate at the same rate and in the same manner as its own particles are vibrating. The surrounding particles set their neighbors into similar vibration, until particles at some distance from the original source are vibrating. It is in this manner that sound vibrations eventually reach the eardrum from a vibrating source.

The fact that bodies producing sound are vibrating rapidly can easily be demonstrated. A tuning fork which is emitting sound will dash the surface of water into a spray if touched to the water; it will also cause a ping pong ball, suspended from a string, to jump violently away when touched with one prong.

Sound Waves. There are several important facts about the transmission of sound vibrations which should be recognized. In the first place, sound vibrations are different from the random vibrations of molecules due to heat; in a body emitting sound, relatively large portions of the body are moving back and forth in unison, and in a regular manner; the same is true of a medium transmitting a sound vibration.

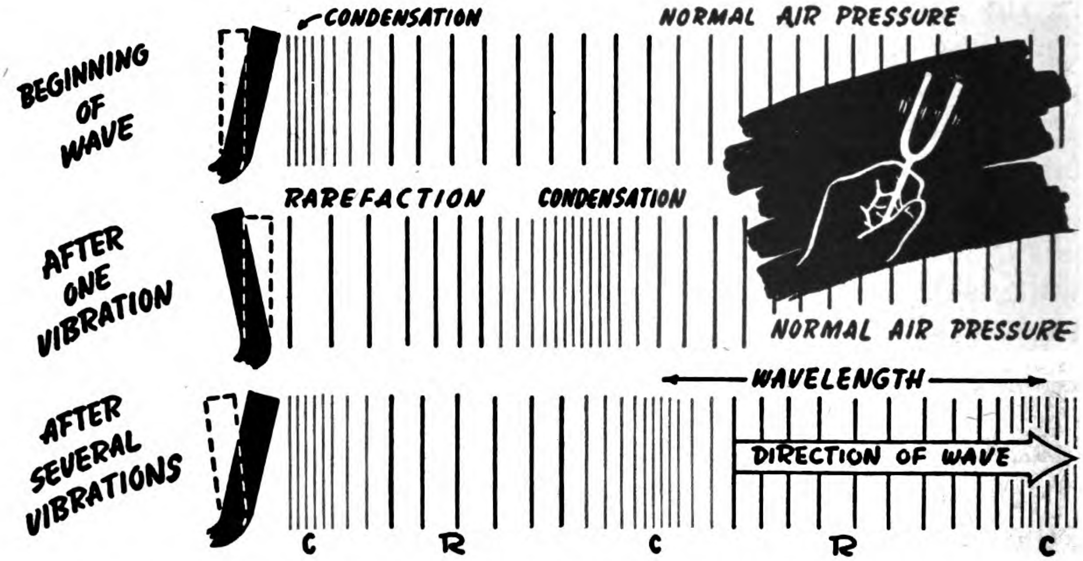
Secondly, the vibrations are propagated as waves of pressure variations in the medium. The particles of the medium move over short distances, but the total effect is that of a wave moving rapidly through the medium.

Thirdly, sound waves are *longitudinal* waves; the particles of the medium move to and fro, but unlike the situation in the rope wave (page 132), the particles move *in the direction* of motion of the wave rather than at right angles to it (*transverse* waves).

Fourthly, like all waves, a sound wave is a fluctuating force, and as such carries energy with it; this sound energy can be made to do work and can be transformed into other forms of energy (such as electrical energy in a microphone).

Finally, sound waves travel only in material media; they cannot traverse an empty space, but are transferred from one material to another only when the two materials are in contact. Thus a bell operating under a bell jar can be heard if air is present in the jar; but if the jar is evacuated by a pump, the sound of the bell disappears, although the bell is still visibly operating.

Production of a Sound Wave. A tuning fork producing a sound wave is shown in the following diagram. Consider one prong which is vibrating so that it moves now to the right, now to the left. As it swings to the right, it pushes the molecules of air alongside it toward the right, and closer to their neighbors; the first row of molecules therefore transmits the push they receive to the next row; this second row then moves to the right giving the third row a push, etc. Any region in which the air molecules are more closely spaced than normal is called a *condensation.*



Production of Sound Waves in Air. Condensations are indicated by red lines.

By the action just described, a condensation starts moving away from the tuning fork prong after its first half-vibration to the right.

The prong now completes one vibration by swinging back to the left, leaving a partial vacuum or region of reduced pressure behind it. The first row of molecules, which by this time has transmitted its original push to its neighbors, now flows back into this region of reduced pressure, or *rarefaction,* produced by the motion of the prong. The neighboring rows, finding the pressure on their left relieved, follow into the rarefaction, but not before they, too, have sent the condensation on its way. In this manner, a rarefaction moves through the air, following on the heels of the advancing condensation.

The prong now swings once more to the right, sending another condensation after the rarefaction, and then back to the left, sending another rarefaction after the condensation. Thus a series of condensations and rarefactions move out through the air surrounding the vibrating prong. Note that a condensation represents a region of increased pressure, while a rarefaction is a region of reduced pressure.

Under the action of the fluctuating pressures produced by the passage of the wave, individual molecules in the air oscillate back and forth, contributing at one moment to a condensation, the next moment to a rarefaction.

This action can be observed in a coiled spring stretched between two fixed supports. When a few coils are compressed and quickly released, a series of visible contractions (condensations) and expansions (rarefactions) will move along the spring. Slow motion moving pictures of this spring would show each coil behaving like a molecule of air when a sound wave passes.

Transmission of Sound. Sound is not transmitted through a vacuum, but does travel through any elastic material, gas, liquid, or solid. The destructive effect of a depth bomb is the result of the transmission of an enormous pressure wave (sound wave) sent out by the exploding bomb; this wave can crush a submarine even at a considerable distance from the actual explosion.

As sound waves in air radiate from a source, in ever-widening spheres, they become weaker because the area over which the original energy is spread becomes greater. The effect is similar to the decrease in illumination as the distance from a light source increases. However, by confining the sound energy to a taut string, its dissipation can be lessened and the sound can be transmitted relatively undiminished over considerable distances, just as a parallel beam of light will illuminate objects at a great distance. Sound waves, like light waves, can also be reflected and focussed.

Velocity of Sound in Air. The velocity of a sound wave in a medium depends on only two things: (1) the elastic constants of the medium, and (2) the temperature of the medium. The velocity is independent of the frequency of the sound and independent of its *amplitude* (strength). The velocity of sound is least in gases, somewhat greater in liquids, and greatest in solids. In steel, for example, the velocity of sound is eleven to fifteen times as great as in air.

The velocity of sound in air is **1090 ft per sec** at 0°C. The speed increases by 2 ft per sec for each degree Centigrade rise in temperature. Thus at 20°C the speed of sound in air is $1090 + (2 \times 20) = 1130$ ft per sec. Using this information, the distance of a lightning flash, or a firing gun can be determined by measuring the time between seeing the flash and hearing the resulting thunder or explosion. (The time of transmission of the light is negligible in comparison with the time of travel of the sound and can be ignored in the calculations.)

TYPICAL PROBLEM

The report of a gun is heard 9.2 seconds after its flash is seen. How far is the gun from the observation point? Air temperature is 15°C.

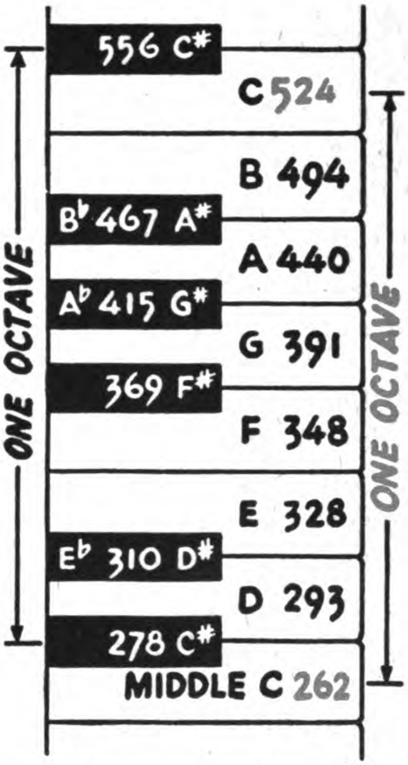
velocity of sound $= 1090 + (2 \times 15) = 1120$ ft per sec
distance = velocity × time; $D = 1120 \times 9.2 =$ **10,300 ft**

Frequency and Wavelength. Since the velocity of sound in a given medium (such as air) is constant except for temperature variations, the higher the frequency of a sound wave the shorter its wavelength. Thus the wavelength of a sound whose frequency is 280 cycles (vibrations) per second, in air at 15°C ($v = 1120$ ft per sec), would be:

$$l = v/f = 1120/280 = \mathbf{4\ ft.}$$

The condensations of such a wave would be 4 ft apart. A sound of frequency twice as great (560 cycles per second) would have half the wavelength—2 ft; the wavelength for 140 cycles would be 8 ft.

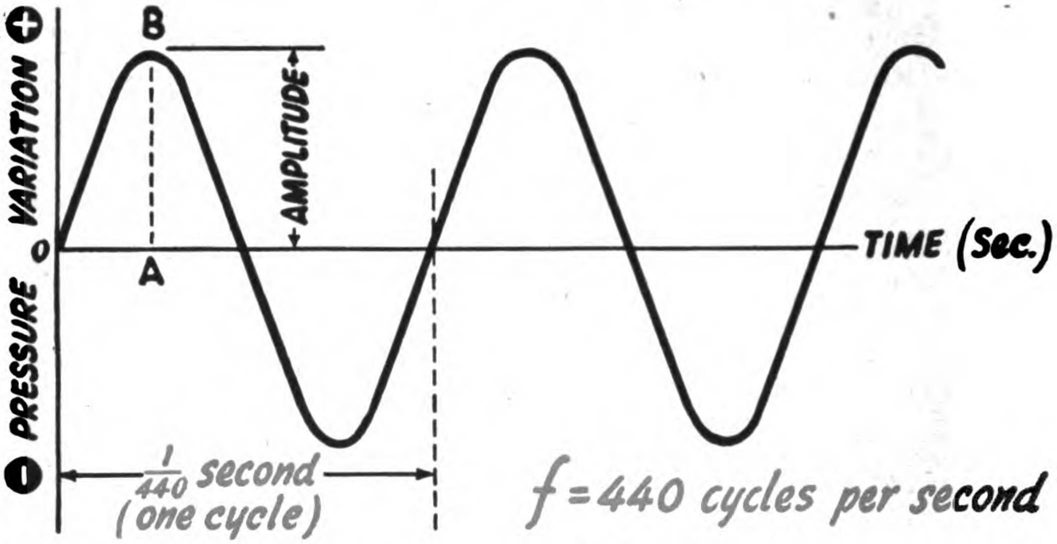
Pitch of a Sound. Every musical sound has a pitch; the sound of a piccolo is said to be *high-pitched;* that of a tuba is *low-pitched.* The pitch or "height" of a tone depends on its frequency. The greater the frequency, the higher the pitch. The human ear responds to tones ranging from a low pitch of about 16 cycles per second to a high pitch of about 20,000 cycles per second; our sensitivity to high tones decreases with age, so that older persons usually cannot hear tones above 12,000 or 15,000 cycles per second. The tone "A" above "middle C" on the piano has a frequency of 440 cycles per second. The frequency of a tone doubles with each *octave;* the "A" an octave higher is 880 cycles; an octave lower it is 220 cycles.



The frequency of a note doubles for each octave of pitch.

Graphic Representation of a Wave. A sound wave can be represented by a graph as can an alternating current (page 119). In the graph of the sound wave, the air pressure is plotted against time, just as the current value is plotted against time for an alternating current. For a tone of a single frequency, a sine curve is obtained (see page 140). (In this graph, zero pressure is taken as the average atmospheric pressure. Positive pressures (condensations) are above atmospheric, negative pressures (rarefactions) are below.)

The maximum change in pressure (*AB* on the diagram) is called the *amplitude* of the wave. The amplitude is also the maximum distance which a molecule in a sound wave moves from its normal position. The strength or loudness of a sound is proportional to its amplitude.

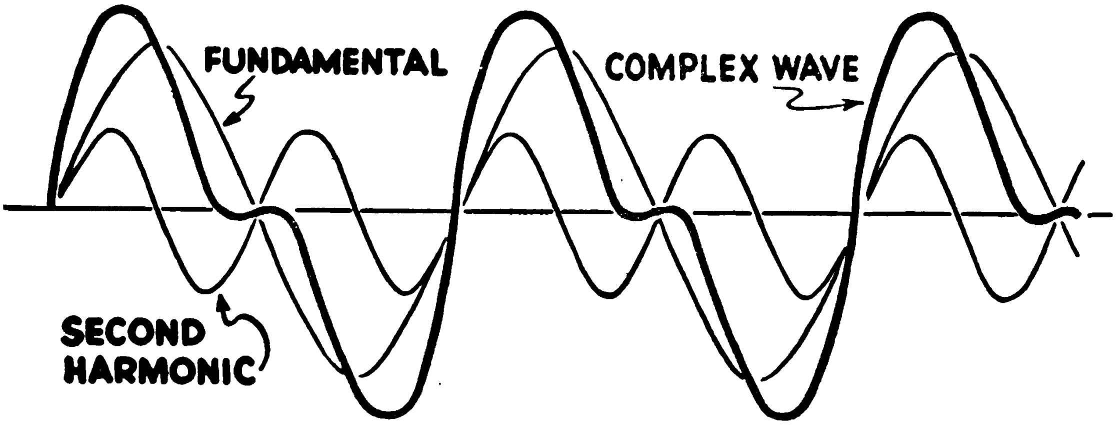


Graph of a Sound Wave. The graph shows how the pressure varies at a point as the sound wave goes by. This is not a picture of the wave in space—sound waves are longitudinal waves, not transverse.

Harmonics or Overtones. No musical instrument ever produces a pure tone, that is, a tone of a single frequency. It actually produces a mixture of tones. The lowest frequency in this mixture is usually the strongest, and is called the *fundamental.* The other tones produced have frequencies which are multiples of the fundamental frequency. These tones are called *overtones* or *harmonics.* A tone whose frequency is twice the fundamental is called the second harmonic; a tone of five times the fundamental frequency is called the fifth harmonic; etc.

Quality of a Tone. With a little practice anyone can learn to distinguish and recognize the instrument producing a given note, because the same note played on different instruments has a different *quality* in each case. For example, nobody would confuse middle C played on the piano with middle C played on a clarinet even though both have the same fundamental frequency. The reason for this is that the tone produced by each instrument varies as to the *number* and *relative strengths* of the harmonics it contains, and therefore varies as to its effect on the ear. There is an interesting experiment in which the higher harmonics of the tones from two different instruments are removed one by one by special electrical filters; as these harmonics are removed, the tones become more and more alike, until, when just the fundamentals are left, the two tones are indistinguishable.

Harmonics give your voice the characteristics or quality which enable your friends to recognize you by your voice alone.



The complex wave shown in red is actually the sum of two simple sine waves, one with twice the frequency of the other.

Graph of a Mixed Tone. The graph of a mixed tone can be found simply by adding the graphs of all its component frequencies. The result is a distorted wave-form as shown above. A musical instrument can be recognized by its wave-form alone, since the wave-form depends on the number and strength of harmonics present. In fact, any wave-form, even of unknown origin, can be broken down into a series of harmonics by a process called *harmonic analysis.* Harmonic analysis plays an important role in determining the causes and corrective measures for vibrations in airplane engines, propellers, and other machines, where the vibration usually has a highly distorted wave-form.

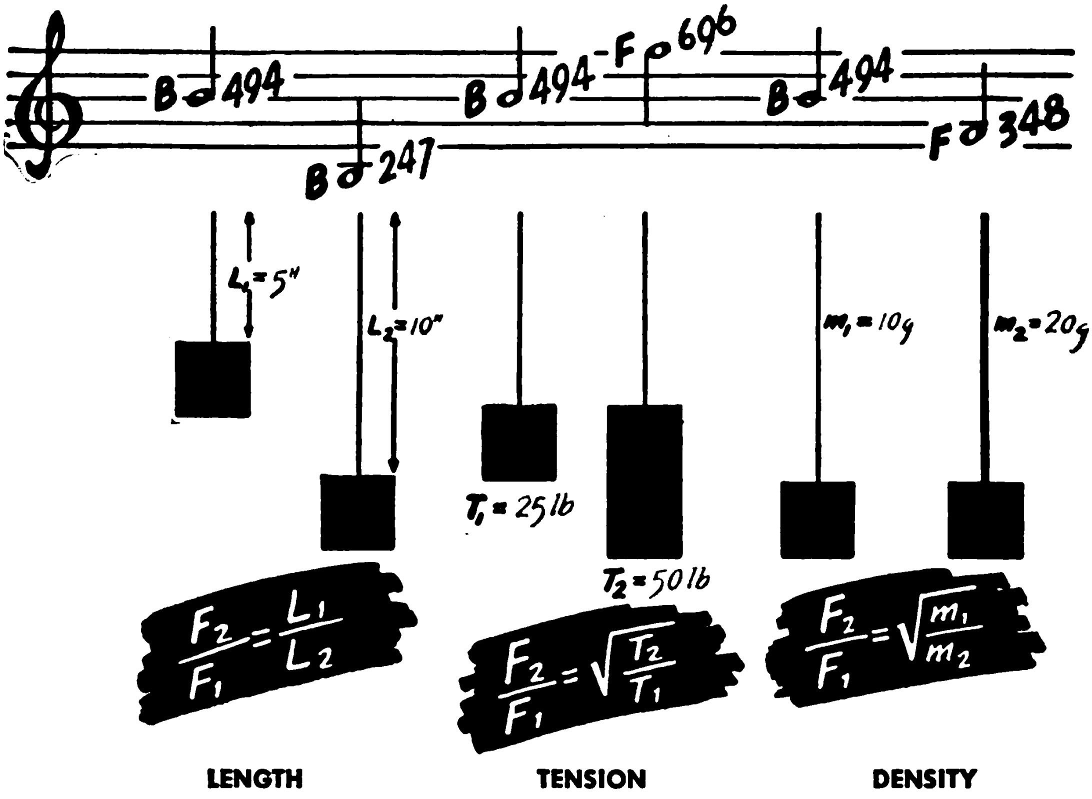
Summary. Every musical sound has three important characteristics:

1. *Fundamental frequency,* which determines the pitch of the sound;
2. *Amplitude,* which determines the loudness of the sound;
3. *Harmonics,* which determine the quality of the sound.

Noises. Sounds in which the frequencies have whole-number ratios to each other are pleasant to the ear, and are called *musical.* Many sounds consist of a mixture of frequencies which have no definite relation to one another. Such a sound has no fundamental frequency, and is called a *noise.*

Laws of Strings. When a violinist wishes to produce a higher note he shortens the effective part of the string by pressing his finger down upon it. A long string vibrates more slowly and gives a lower note than a short string, provided other conditions are held constant. Doubling the length of a string cuts its frequency of vibration in half and lowers the pitch of the note produced by one octave. The *first law of strings* states that the frequency varies inversely as the length of the string.

The pitch of a string can also be raised by tightening the string, or lowered by loosening it. Thus the pitch of a tone can



Factors Determining the Pitch of a String. The weights attached to the lower ends of the strings represent tension. The numbers in red (opposite the notes) are frequencies of vibration. In the first pair of strings, all factors are the same except length. Notice that the string which is twice as long has half the frequency—which checks with the formula given. In the second pair of strings, the tension is varied. The numbers in red again satisfy the formula given. In the third pair of strings, the unit weight (m) of the string is changed. Check the values in red against the formula.

be controlled by varying the tension upon the string which produces it. When the tension of the string is made four times as great the pitch is doubled; if it is made nine times as great the pitch is tripled, etc. The *second law of strings* states that the frequency varies directly as the square root of the tension.

Heavy strings give low notes; light strings give high notes. The *third law of strings* states that the frequency of a string varies inversely as the square root of its weight per unit length.

Reflection of Sound. The intensity of sound in a room is partially maintained by the back and forth reflection of sound waves. In small rooms the reflected waves return too soon to be heard as separate sounds, but they do produce an effect called *reverberation.* Some reverberation is desirable, because without it speech and music seem dull and lifeless. If a reflected sound strikes the ear more than a tenth of a second later than the original sound, both sounds are heard separately and an *echo* is produced. Echoes are produced if the reflecting surface is 55 feet or more from the ear. Echoes and excessive reverberation can be eliminated by padding the ceilings and walls with absorbing materials which reduce the amount of reflection.

TYPICAL PROBLEM

Five seconds after a sound is sent out from a ship in the north Atlantic, an echo is heard due to reflection from an iceberg. How far away is the iceberg if the temperature of the air is 5°C?

$$\text{Speed of sound at } 5^\circ\text{C} = 1090 + (2 \times 5) = 1100 \text{ ft per sec}$$

$$d = vt;\ d = 1100 \times 5 = 5500 \text{ ft}$$

$$\frac{5500 \text{ ft}}{2} = \mathbf{2750\ ft,\ distance\ to\ iceberg}$$

Sonic Sounding. The reflection of sound waves is used in many determinations of depth and distance. For example, the depth of the ocean floor is measured by sending a sound pulse down through the water, and noting the time interval when the echo is returned. It has recently been shown that bats (which are blind) guide their flight around obstacles by means of echoes of high-pitched sounds which the bats produce while in flight. These sounds emitted by bats are beyond the human audible

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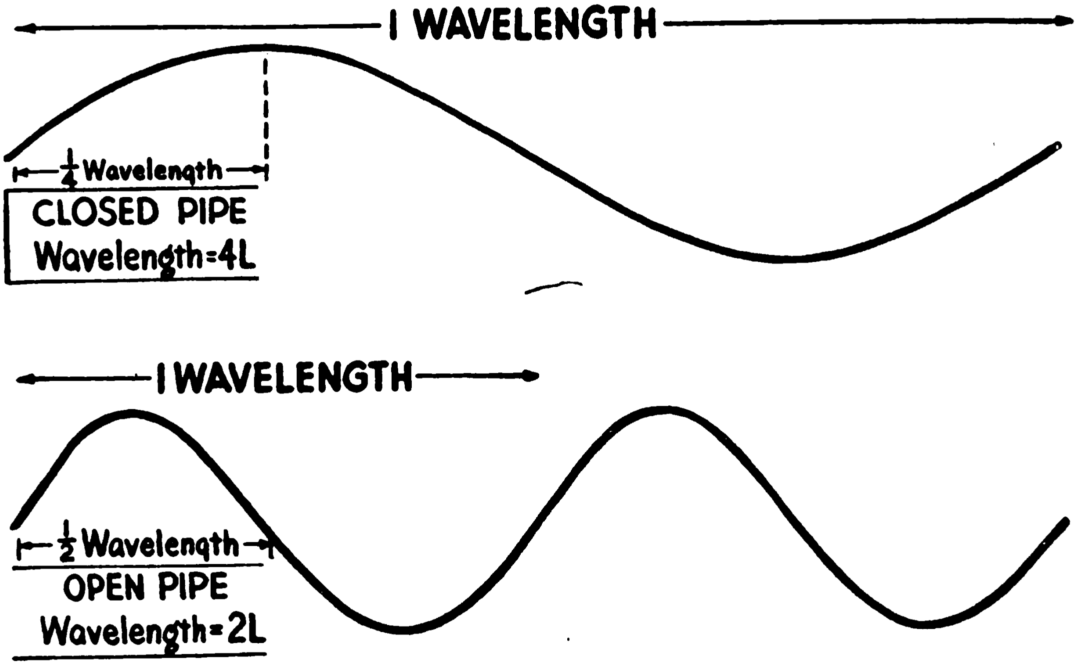
range, having frequencies of about 50,000 cycles per second. Sounds which are too high-pitched for human ears to hear are called *supersonic.*

Forced Vibrations. If the handle of a vibrating tuning fork is pressed against the table, the volume or amplitude of the sound will increase. The table has been forced to vibrate at the frequency of the tuning fork, thereby increasing the amount of surface radiating sound. The sounding board of the piano and the thin wood box of the violin are used to increase the strength of all the tones produced by the strings, by means of these *forced vibrations.*

Sympathetic Vibrations and Resonance. Every body, freely suspended so that friction will not "damp out" its vibrations, will vibrate at a particular frequency when it is struck. This is called its *natural frequency of vibration.* When two vibrating bodies have the same natural frequency, they are said to be in *resonance.* If one vibrating body is touched to or brought near another with the same natural frequency, the second will begin to vibrate at that frequency; the amplitude of the induced vibration will generally be greater than that in ordinary forced vibrations because each condensation from the "exciting" body arrives in time to reinforce the condensation of the responding body, thus building up a strong vibration. The total volume of sound is also increased because condensations and rarefactions from both bodies are in step and strengthen each other.

Vibrations induced in a body because of resonance are called *sympathetic vibrations.* A picture wire or windowpane may be excited to sympathetic vibration when certain notes are played on a piano or come over the radio. If one of the keys of a piano is held down, and the corresponding key an octave lower is struck sharply and released, the string being held open will be heard sounding at its own frequency. The second harmonic of the lower tone, being in resonance with this string, has set the string vibrating by sympathetic vibration. By holding each of the piano keys down in turn, and striking the same note each time, all the harmonics of that note can be discovered by this method of sympathetic vibrations.

Resonance of Air Columns. Solid bodies are not the only ones with natural frequencies. The air in a bottle, or in a long tube, has a definite natural frequency, and such a body of air will vibrate sympathetically when excited by a sound of its frequency. The "sound of the sea" in a sea-shell is produced by resonance of the air in the shell with some frequency in the many sounds around us at all times.



The Laws of Pipes. A closed pipe emits or resonates with a sound whose wavelength is four times the length of the pipe. The wavelength for an open pipe is only twice the length of the pipe. The longitudinal sound wave has been represented as a transverse wave, in order to show the distance between successive condensations.

Laws of Pipes. Pipes such as those of the pipe organ are described as either open or closed pipes. *Open pipes* are open at both ends and *closed pipes* are open at only one end. Various wind instruments are really pipes in which the sound is due to the fact that the air column within the pipe acts as a resonator. In wind instruments, this resonator is set in vibration by a reed (as in the saxophone) or by blowing air across a sharp edge or opening (as in the flute or organ pipe), or by forcing air through a narrow opening (as that formed by the lips of the cornet player). In speech the air enclosed by the nasal passages, mouth, and head cavities acts as the resonator for the vibrations caused by air forced between the vocal cords.

A closed pipe gives reinforcement to a sound when the length of the pipe is one-fourth the wave length of the sound. An open pipe gives reinforcement to a sound when the length of the pipe is one half the wave length of the sound. Thus an open pipe produces a note whose frequency is double (an octave higher than) that produced by a closed pipe of the same length.

When a hole is bored in a pipe, the effect is the same as if the pipe were cut off at that point. This explains the use of holes or "stops" in wind instruments. These holes are opened or closed by means of the fingers or valves in order to change the resonant length of the pipe, and hence alter the pitch of the tone produced.

TYPICAL PROBLEMS

The frequency of a tuning fork is 256 vps, and the temperature is 19°C. Find the length of the closed pipe necessary to give resonance.

velocity of sound at 19°C $= 1090 + (2 \times 19) = 1128$ ft/sec
$v = n \times l$; $1128 = 256 \times l$; hence, $l = 4.4$ ft, wavelength

$\frac{1}{4}l$ = **1.1 ft, length of closed pipe giving resonance**

What is the frequency of a tuning fork if a closed pipe 18 inches long reinforces the sound emitted by the fork? (The temperature is 22°C.)

wavelength $= 4 \times 18$ inches $= 72$ in $= 6$ ft
$v = n \times l$; $1134 = 6 \times n$; hence, $\mathbf{n = 189}$ **vps**

Beats. If two notes of somewhat different frequencies are sounded together, their waves periodically get in step and reinforce each other, then get out of step and interfere with each other. The result is a pulsating or throbbing sound. These pulsations are called *beats.* For example, if two tunings forks, one with a frequency of 200 and the other with a frequency of 210, are sounded together, they are in step and out of step 10 times each second, and the ear hears 10 throbs each second. The number of beats is always equal to the difference in the frequencies of the two notes.

If the number of beats per second is about 5 or 6, the sound is not very disagreeable. If this number is increased to about 30, the discord is very unpleasant; when the number of beats is increased still further to about 60, the sound again becomes agreeable. Harmonies and discords in music depend upon the beats produced by combinations of various tones.

QUESTIONS

1. What are the three characteristics that identify a sound?

2. How do you account for some objects in a room vibrating when certain notes are sounded on a piano or over a radio?

3. Explain the action of (*a*) a megaphone; (*b*) an ear trumpet.

4. How does the violinist produce (*a*) a higher note, (*b*) a louder sound when playing on a given string?

5. State whether each of the following statements is true or false, and give a reason for your answer. (*a*) High-pitched tones and low-pitched tones have the same velocity in air. (*b*) A stretched wire and a tuning fork, when sounded together, produce 8 beats per sec. If the frequency of the fork is 320 vps, the frequency of the wire must be 328 vps. (*c*) The speed of sound in air at 40°C is 1130 ft per sec. (*d*) Echoes are caused by the interference of sound waves.

PROBLEMS

1. A boat whistle is heard 3.5 seconds after it is seen to blow. How far away is the boat? (Temperature, 10°C.) Ans. 3885 ft

2. How long after a whistle is blown, will an echo be heard from a cliff 2 miles away, on a day when the temperature is 25°C? Ans. 18.5 sec

3. How long after a stone is dropped from the top of a building 576 ft tall will the sound of its striking the ground be heard if the air temperature is 31°C? (The time for the stone to fall to the ground is obtained from the relation $d = \frac{1}{2}gt^2$.) Ans. 6.5 sec

4. (*a*) When the temperature is 15°C what is the wave length of middle C whose frequency is 256? (*b*) What would the wave length of this note be at 30°C? Ans. (a) 4.38 ft (b) 4.50 ft

5. What is the frequency of a tuning fork whose sound is reinforced by a closed tube 12 inches long when the temperature is 20°C? Ans. 282.5 vps

6. (*a*) What is the length of a closed pipe that resonates to a note whose frequency is 565 vibrations per second (temperature 20°C)? (*b*) What should the length of a closed organ pipe be to give this note? (*c*) What should the length of an open organ pipe be to give this note? Ans. (a) 6 in (b) 6 in (c) 12 in

7. A stretched string has a frequency of 256 vps when the tension is 16 lb. What will be the frequency if (*a*) the length is reduced to one-half? (*b*) The tension is increased to 64 lb? (*c*) Both (*a*) and (*b*) are done together? Ans. (a) 512 vps (b) 512 vps (c) 1024 vps

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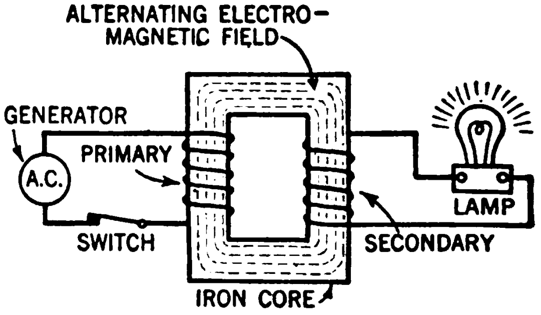
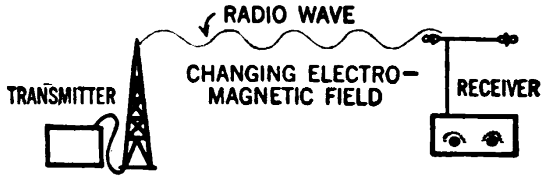
ELEVEN— RADIO AND ELECTRONICS

The Basic Idea in Radio Communication. The principle of radio communication is illustrated by the simple transformer shown in the diagram. By closing the switch in the primary circuit, the lamp in the secondary circuit is illuminated; opening the switch puts out the light. There is no direct wire connection between the switch and the lamp; the energy is transmitted to the lamp by an alternating electromagnetic field in the core of the transformer. This is a simple form of wireless control of one circuit (the secondary) by another circuit (the primary).





In wireless communication over large distances, the principle remains the same. An alternating current generator (the transmitter) sets up an alternating electromagnetic field everywhere in space, thus acting like the primary of a transformer. A secondary, the receiver, absorbs energy from this field and uses it to operate or control some signalling device such as a loud speaker.

The electromagnetic field of a radio transmitter does not come into existence instantaneously everywhere in space; it is propagated through space as a wave traveling with the speed of light. As pointed out previously radio waves and light waves are identical in nature, differing only in wavelength.

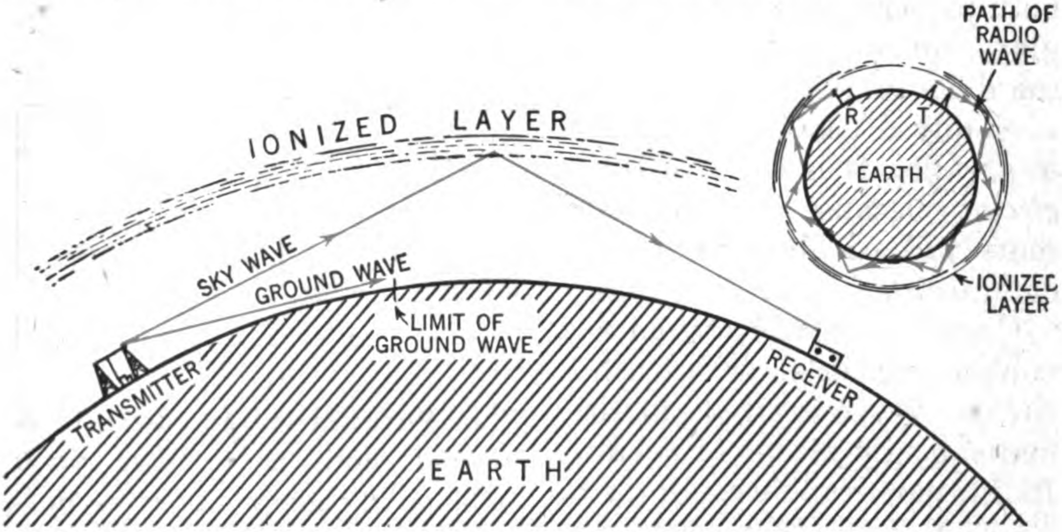
Frequency and Wavelength. As in other waves, *frequency* × *wavelength* = *velocity*. In radio waves,

frequency in kc × wavelength in meters = 300,000.

Properties of Radio Waves. As radio waves radiate away from the transmitter, their strength decreases, just as the intensity of light diminishes as you recede from the source. For communication over long distances, large amounts of energy must be put into the radio wave. The *transmitting antenna* is a device, usually in the form of a long wire or tall metal tower, which is designed to radiate radio waves efficiently. The *receiving antenna* is likewise designed to *absorb* a maximum amount of energy from the radio wave as it passes.

Most antennas radiate waves in all directions, but emit the strongest waves in just a few definite directions. For example, an antenna usually sends out a strong *ground wave*—one which starts out parallel to the ground. This ground wave tends to follow the curvature of the earth. It can be received up to several hundred miles for long or low frequency waves (100 to 1600 kilocycles per second), but it has a very limited range when the frequency is much higher.

In addition to the ground wave, an antenna usually radiates one or more strong signals upwards at an angle to the horizontal. Such a wave is called a *sky wave.* If the frequency is less than about 15,000 kilocycles, this sky wave will usually be reflected back to earth by the Heaviside and other ionized layers of the upper atmosphere. In fact, by repeated reflection between the earth and these ionized layers, a single wave may circle the globe before being received. It is the reflection of sky waves that makes long-distance radio communication possible.



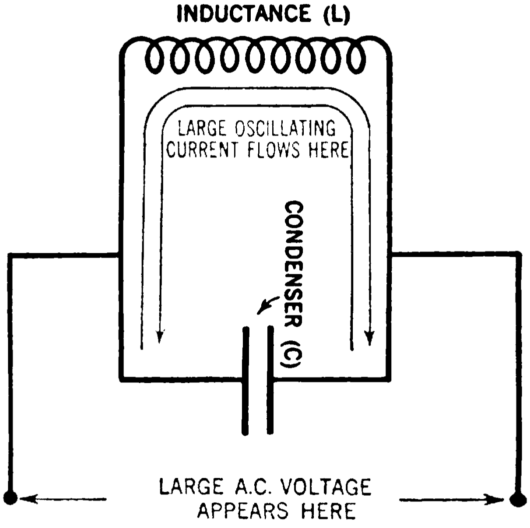
The red lines show some of the possible paths of a radio wave.

If the frequency is above 15,000 kc, the waves (called *ultra-high frequency* waves) act very much like light waves. The ground wave does not follow the earth's curvature and hence cannot be received beyond the horizon. The sky wave, on the other hand, is not reflected by the ionized layers, and continues on into space. While not suitable for long-distance communication, ultra-high frequency waves are ideal for plane-to-ground communication, "walkie-talkie" sets, and *radar* (RAdio Detection And Ranging). In radar, an ultra-high frequency radio beam is used like a searchlight to detect enemy aircraft or ships by reflection. Unlike searchlights, the radar beam penetrates fog and clouds, and also gives the distance of the reflecting object.

RESONANCE AND TUNING

The Tuned Circuit. The problem at the transmitter is to generate an alternating current of a definite high frequency. At the receiver, one particular radio signal must be selected from the thousands which fill the air at all times. In accomplishing both purposes, the same circuit plays an important part. As the diagram shows, this circuit is simply a condenser and coil in parallel. It is called a *tuned circuit* because electric currents will oscillate in it at a definite frequency.

On page 128, the current and voltage relationships in such a circuit were derived mathematically by means of vectors. In this paragraph we will try to see what is taking place physically inside the circuit. Imagine first that the condenser and coil are disconnected, and the condenser then charged by a battery or DC generator. Then suppose the charged condenser is connected to the coil. Immediately electrons (current) will begin to flow from one condenser plate to


INDUCTANCE (L)
LARGE OSCILLATING CURRENT FLOWS HERE
CONDENSER (C)
LARGE A.C. VOLTAGE APPEARS HERE

The Parallel-Tuned Circuit. A current tends to oscillate at a definite frequency inside the parallel circuit, while a large AC voltage appears between the terminals of the circuit.

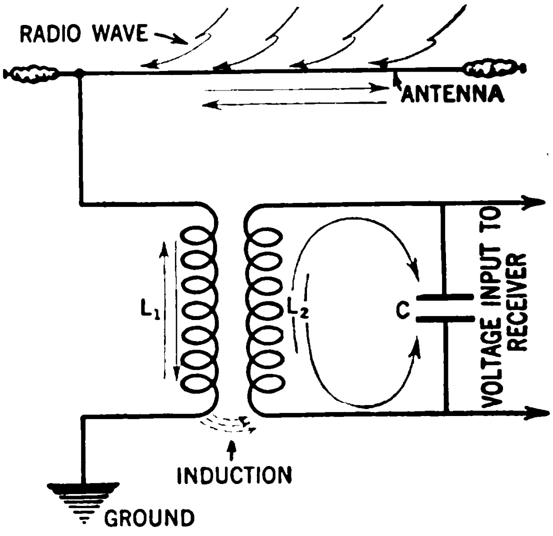
the other through the coil. But the inductance of the coil tends to prevent the building-up of this current, thereby delaying the discharge. Nevertheless, the current continues to increase in strength as long as there is an unbalance of charge on the condenser. Eventually the condenser will be discharged completely, but a large current will be flowing through the coil at that time. The inductance now tends to prevent the slowing down of this current, so that by the time the current is brought to zero, the condenser is fully charged in the opposite direction. As soon as the current reaches zero, the condenser begins to discharge in the other direction, and the whole cycle is repeated. This is exactly analogous to the action of the balance wheel of a clock, or a swinging pendulum. The force tending to produce motion reaches zero just as the velocity reaches a maximum, and inertia keeps the body going until a strong force builds up in the opposite direction and reverses the swing. If it were not for frictional losses, a pendulum would oscillate indefinitely; if it were not for resistance losses, the current in a tuned circuit would oscillate indefinitely, once started.

The frequency of oscillation depends on the values of the inductance L and capacitance C in the circuit. A larger L would delay the condenser discharge and hence reduce the frequency; likewise, a larger C would take longer to charge and discharge and would also reduce the frequency. It turns out that the natural frequency of oscillation of the parallel circuit is the same as its resonant frequency described on page 147:

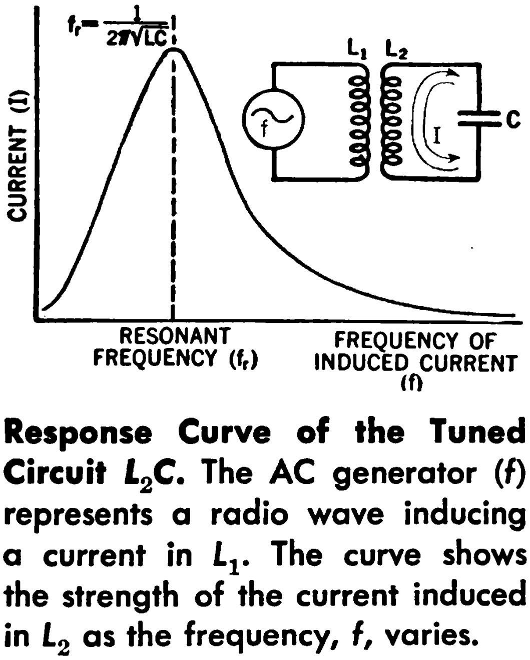
$$\text{frequency of oscillation} = \frac{1}{2\pi\sqrt{LC}}$$

We see now why this is called the resonant frequency of the circuit. It is the circuit's natural frequency of oscillation, just as the resonant frequency of a tuning fork is its natural frequency of vibration.

Electrical Resonance. The typical antenna circuit of a radio receiver is shown in the next diagram. A radio wave passing the antenna induces an alternating current in the antenna at the frequency of the radio wave. This high-frequency (radio-frequency or rf) current flows between antenna and ground through the coil L_1. This current in turn induces another current, by transformer action, in coil L_2 of the tuned circuit L_2C. The antenna current is very weak, so that ordinarily it would induce a small voltage in L_2. If, however, the frequency of the antenna current is the same as the resonant frequency of the tuned circuit, a very large oscillating current will be set up in the tuned circuit. The effect is exactly similar to sympathetic vibration or resonance in sound (p. 144), or resonance in any vibrating system. Under these conditions the tuned circuit is said to be *in resonance* with the antenna current and with the radio wave producing it. At any other frequency of the antenna current, a current of that frequency will still be induced in the tuned circuit, but its magnitude will be much less than it was at resonance; the result is now similar to forced vibration rather than sympathetic or resonant vibration.



The tuned circuit of a receiver tends to resonate with the AC currents produced in the antenna circuit by a radio wave of the proper frequency.



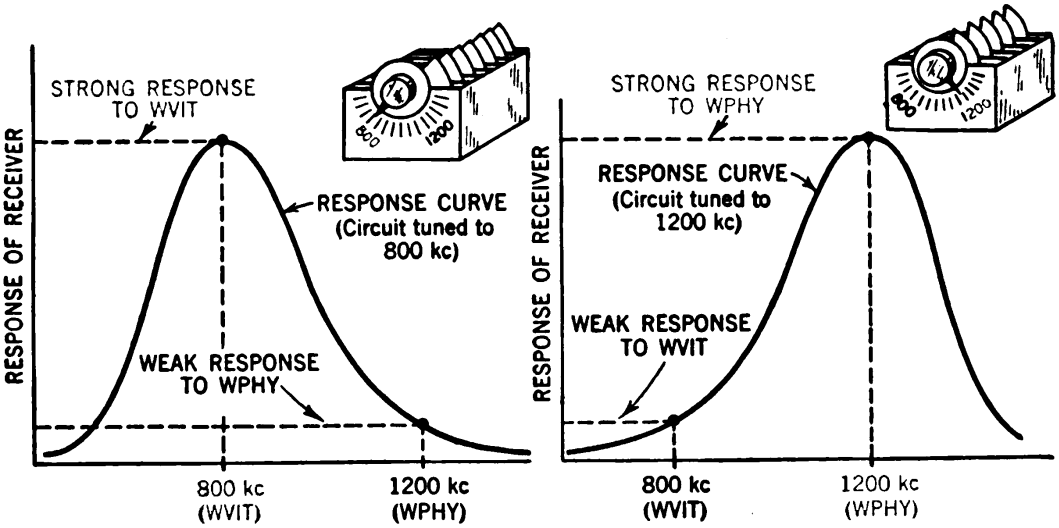
Response Curve of the Tuned Circuit L_2C. The AC generator (*f*) represents a radio wave inducing a current in L_1. The curve shows the strength of the current induced in L_2 as the frequency, *f*, varies.

Selectivity of a Tuned Circuit. If a graph of the current in the tuned circuit is plotted against frequency of antenna current (the latter assumed to be constant in amplitude), a curve similar to that shown will be obtained, with a pronounced "peak" at the resonant frequency. It is seen that frequencies much removed from the resonant frequency produce only small currents in the tuned circuit. Thus a radio wave of the resonant frequency will produce a strong signal in the receiver; other radio waves will produce extremely weak signals, which ordinarily will not be strong enough to operate the earphones or speaker. The only difficulty arises when two or more signals, all close to the resonant frequency, act on the antenna at the same time. In that case each wave produces an audible signal, resulting in interference.

Such interference can be minimized by making the response curve as sharp as possible, so that only at exact resonance or very close to it will an audible signal result. A tuned circuit with a sharply peaked response curve is said to be highly *selective.* Selectivity of a receiver is a measure of its ability to distinguish between two signals close in frequency. Selectivity of a tuned circuit is improved by reducing the resistance of its elements.

Tuning. If either the condenser or coil of the tuned circuit is made variable, the circuit can be tuned at will to any desired frequency—thus bringing it into resonance with any radio wave. This is exactly what we do when we turn the tuning knob of a broadcast receiver. Look behind the panel of a radio while tuning it from one station to another and you will see the movable plates of a variable condenser rotating and thereby changing the capacitance of the condenser.

Note that currents are being produced in the antenna by all radio waves. The tuned circuit simply selects the desired one for



How a Radio Receiver Is Tuned. At the left, the set is tuned to Station WVIT (800 kc). At the right, it is tuned to Station WPHY (1200 kc).

amplification in the receiver by moving the resonance "peak" until it coincides with the frequency of the desired wave.

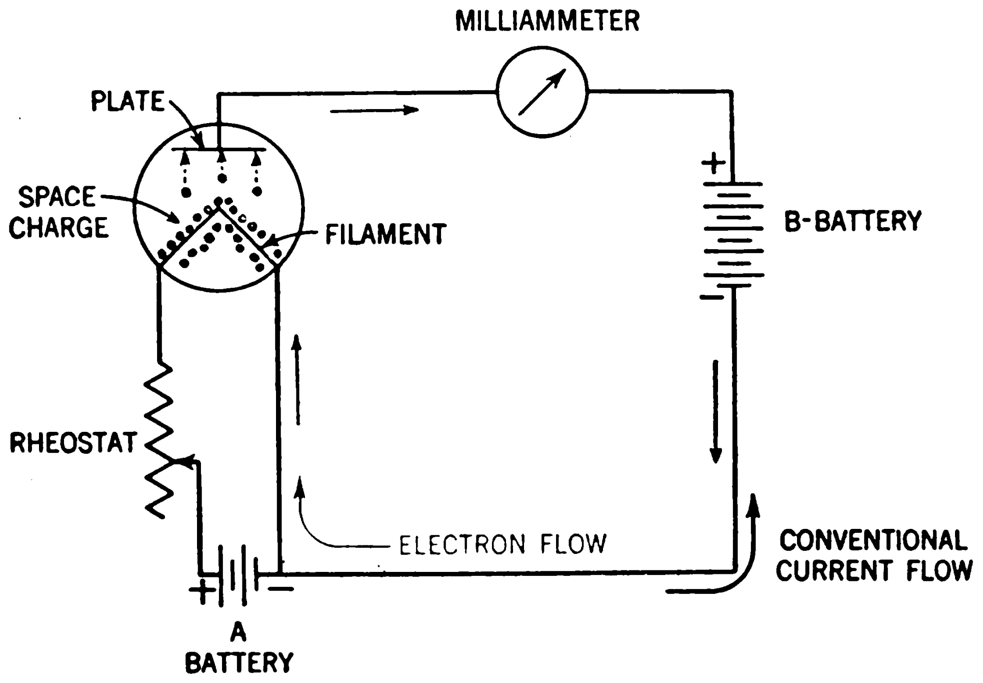
VACUUM TUBES

Thermionic Emission. Before proceeding further with the discussion of generation and detection of radio waves, a second fundamental device in modern radio circuits, the vacuum tube, must be explained. The vacuum tube makes use of the emission of electrons from hot bodies. When any substance is heated sufficiently, some of its electrons acquire enough energy to leave the surface. This emission of electrons as a result of increased temperature is called *thermionic emission.*

As electrons leave the body, the body acquires a positive charge and attracts the emitted electrons back to the surface. Thus electrons are continuously rising from and falling back into the surface of the emitting body. While no individual electron remains in the space around the body very long, there is always a cloud of electrons surrounding the body. This cloud of electrons is called the space charge. Electrons are always dropping out of the space charge, but are at the same time replaced by others being emitted. Thus the number of electrons in the space charge remains constant as long as the temperature remains the same. An increase in temperature increases the number of electrons present in the space charge.

The Diode (Two-Element Vacuum Tube). The simplest vacuum tube consists of a glass or metal shell, evacuated of almost all gases, and containing two elements—a *filament* or *cathode,* and a *plate.* The filament is a resistance wire, like the filament of an electric light bulb, but treated so that it is capable of a high thermionic emission. The two ends of the filament are brought out to terminals in the base of the tube, so that an electric current can be passed through the filament, thus heating it and causing it to emit electrons. The plate is simply a metal cylinder or disc supported at a distance from the filament, and connected to a third terminal in the base of the tube.

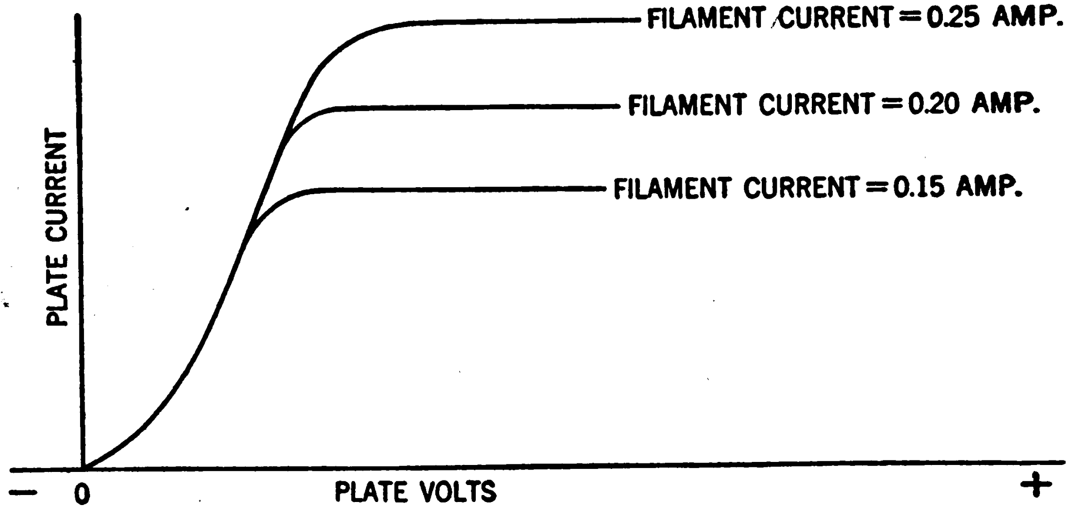
When the filament is connected to a battery or other power supply (usually between 2 and 6 volts), the filament is heated, emits electrons, and produces a space charge around it. If the plate is now connected to the positive terminal of a DC power source (such as a battery), and the negative terminal of the



A Diode in Operation. The rheostat controls the temperature of the filament.

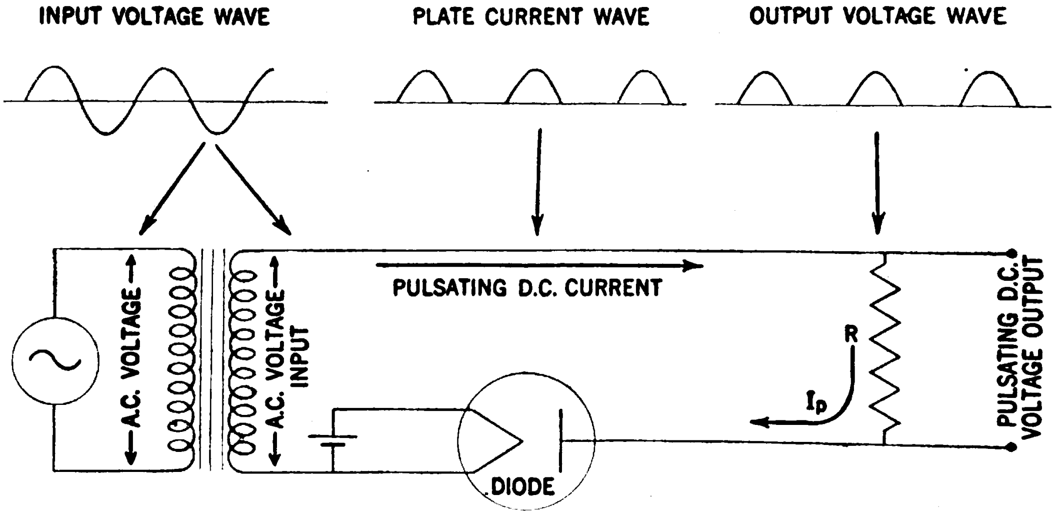
power source connected to one end of the filament, a difference of potential will be set up between the plate and the filament. The positive plate will then attract to it some of the electrons in the space charge, and electrons will flow from the plate through the battery, into the filament, and back into the space charge. This electron flow is of course an electric current. (By the convention of current flow, the current is said to flow from the battery toward the plate in the external circuit; the vacuum tube gives proof, however, that the flow of electrons which really constitutes an electric current is in the opposite direction.)

Characteristic Curves of the Diode. It is customary to represent the plate potential by the symbol E_p, the current in the plate circuit by I_p, and the filament heating current by I_f. As E_p increases positively from zero, I_p also increases, as the plate draws more and more of the electrons from the space charge. At some value of E_p, the attraction of the positive plate will be so great that *all* the electrons emitted by the filament will be flowing to the plate. The reservoir of electrons which the space charge represents will be supplying its maximum flow. If E_p is increased further, no change will take place in I_p. This maximum value of



Characteristics of the Diode

I_p is called the *saturation current.* If, however, the filament temperature is raised by increasing I_f, more electrons will be made available, the saturation current will increase, and will be obtained at a higher value of E_p. These facts about a vacuum tube can be presented most clearly and most compactly by a set of graphs called the *characteristic curves* (or simply, the characteristics) of the tube. In the case of the diode, we usually plot I_p against E_p for various values of I_f. As can be seen from these

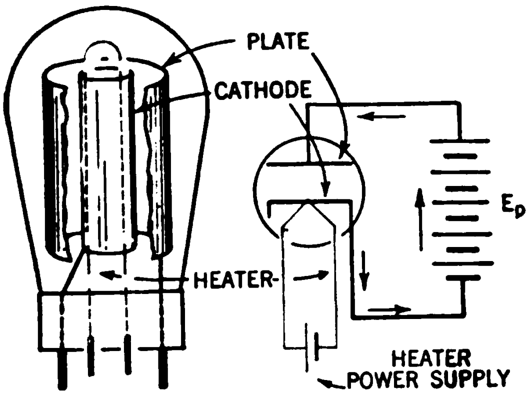


Changing AC to DC with a Diode Rectifier

curves, I_p is proportional to E_p until saturation is approached, when the curve flattens off to a constant value. The plate current is zero for all negative values of plate voltage.

The Diode as a Rectifier. Since plate current will flow through a vacuum tube in only one direction (from plate to filament—electrons flowing from filament to plate), the diode can be used as a rectifier of AC. The AC voltage is applied to the plate through a resistor, as shown in the wiring diagram. The negative half-cycles are eliminated, and a pulsating DC current flows in the plate circuit. This current flowing through the load resistor, *R*, produces a pulsating DC voltage across the resistor. This voltage can be used as a source of DC power. (See diagram, p. 156.)

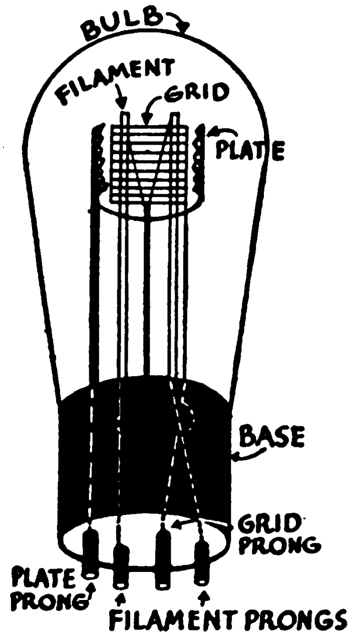
Indirectly Heated Cathodes. In many tubes, the cathode is a cylindrical sleeve surrounding, but not touching, the filament. The filament is used only to heat the cathode, and plate current flows between cathode and plate through a separate cathode connection in the base of the tube. This construction completely isolates the filament heating current from the plate circuit, a desirable result when the filament is heated by an AC current (as in AC-operated radios). If the filament current is not isolated in this way on AC, a 60-cycle fluctuation will be introduced into the plate current, producing a hum in the loud speaker.



The heater of an AC tube is isolated electrically from the plate-cathode circuit.

The Triode (Three-Element Vacuum Tube). In 1906, Lee DeForest, an American, discovered that the usefulness of a vacuum tube can be enormously increased by introducing a third element, the grid, between cathode and plate.

The grid is a spiral of wire wound in the space between cathode and plate, and connected to a separate prong in the tube base. By applying voltages between grid and cathode (as was done between plate and cathode in the diode) the plate current can be controlled, without changing the plate voltage. When the



Construction of the Triode

grid is made more positive, it helps the plate attract electrons, thereby increasing the plate current; when the grid is made more negative, it repels electrons, making it more difficult for electrons to reach the plate and thereby reducing the plate current. Because of the wide spacing of the grid wires, these wires do not physically impede the flow of electrons to the plate—they simply control the flow through the action of an electrostatic field.

Because the grid is nearer the space charge, it has a greater influence over the electrons than has the plate. Consequently a small change in grid voltage produces a much larger change in plate current than the same change in plate voltage would produce. For example, a change of 1 volt in grid voltage may produce the same change in plate current as a 10-volt change in plate voltage. Such a tube has an *amplification factor* of 10.

Very little current flows in the grid circuit. This means that very little energy or power is required by the grid. Thus with small amounts of power relatively large currents and powers can be controlled in the plate circuit. The triode can therefore be used as a *power* amplifier as well as a *voltage* amplifier.

Triode Characteristics. The graphs (p. 159) show how the plate current of a typical triode varies as the grid voltage varies, for various fixed values of plate voltage. These curves were obtained by applying a fixed voltage to the plate and reading the plate current on a milliammeter as various grid voltages were applied to the grid. The data was collected for each value of plate voltage shown. These characteristics reveal the following points.

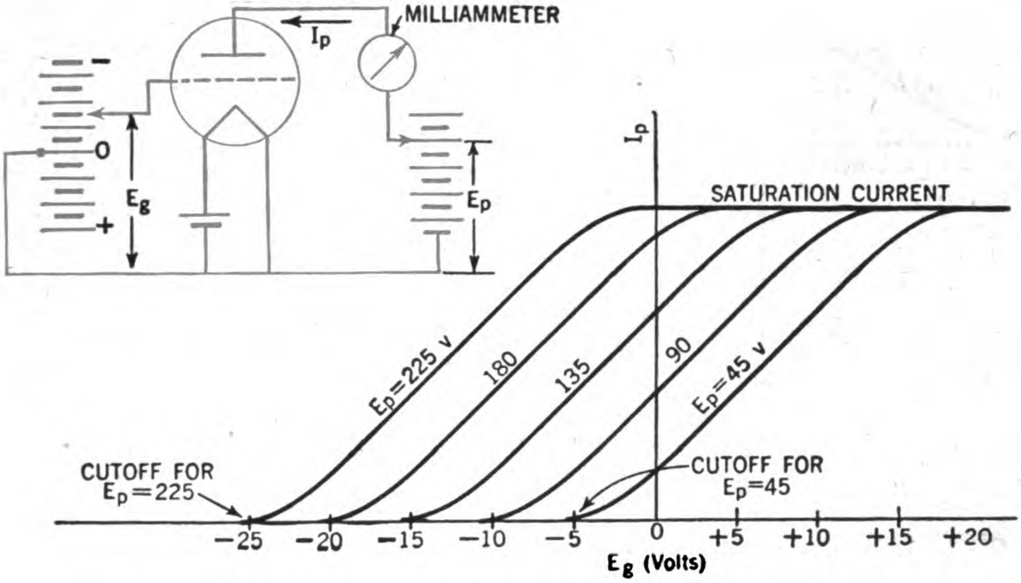
1. For each value of E_p, there is a definite grid potential which will reduce I_p to zero; this point is called *cutoff,* and the value of E_g that produces it is called *cutoff bias.*

2. The larger E_p is, the more negative E_g must be to produce cutoff.

3. As E_g is made less negative, I_p increases.

4. When E_g is made sufficiently positive, saturation occurs. The saturation value of I_p is the same for all values of E_p.

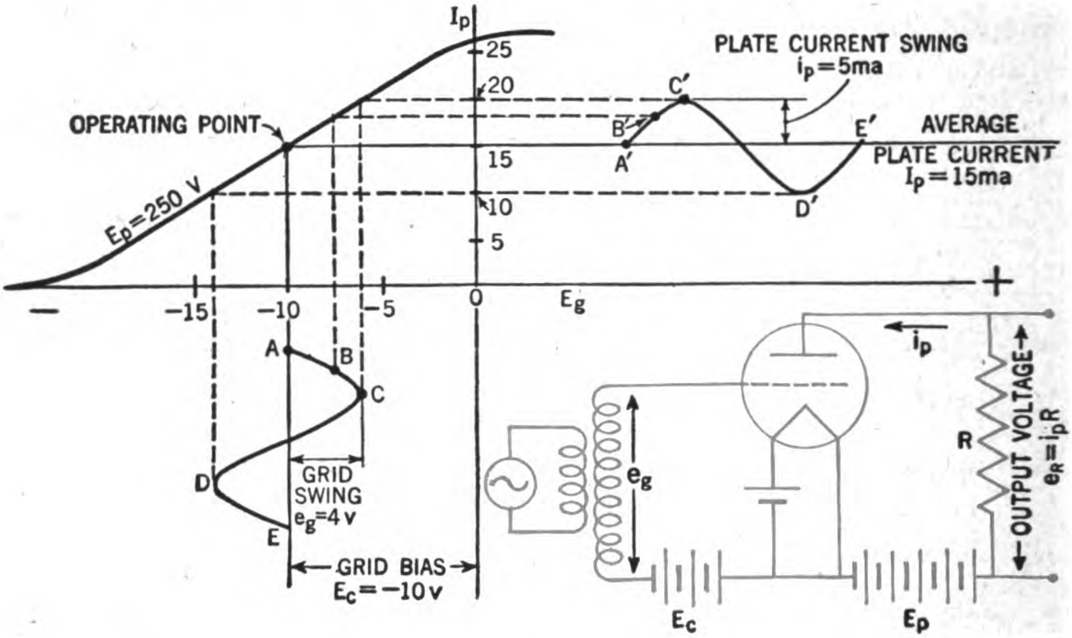
5. The curvature of the characteristics indicates that the effect of E_g in controlling I_p is not uniform; only in the central, straight-line part of the curves do equal changes in E_g produce equal changes in I_p.



Triode Characteristics

Effect of Signal Voltage on Plate Current of Triode. A triode is frequently used to reproduce E_g (grid voltage) variations in amplified form across a resistance or impedance in the plate circuit. This is illustrated in the diagram on page 160. The input voltage is called the *signal* or *excitation* and is represented by e_g.

Assume that the fixed grid voltage or *bias* (E_c) is -10 volts and that the signal voltage (e_g) is a sine wave emf of 4 volts peak value. When E_g varies from point *A* to *B*, the effect is to increase I_p from the value at *A′* to the value at *B′*. As E_g swings through point *C* and back to point *D*, I_p increases to *C′* and decreases to *D′*; when E_g is at point *E*, I_p reaches its average value of *E′*; etc. The output plate current variations are plotted and show a corresponding sine wave form. Similarity of input and output waves represent good fidelity, that is, faithful reproduction. Only when the tube is operated along the straight-line part of the characteristic is this obtained. If operation extends to saturation at one end or cutoff at the other, the output wave will not match the input wave; *distortion* is thus introduced.



The varying plate current flowing through the resistance in the plate circuit produces a voltage drop that varies similarly. This voltage variation is much larger than the variation of the signal applied to the grid. Hence, amplification has been obtained. The voltage amplification or *gain* of the tube and circuit (called a *stage*) is expressed by the formula:

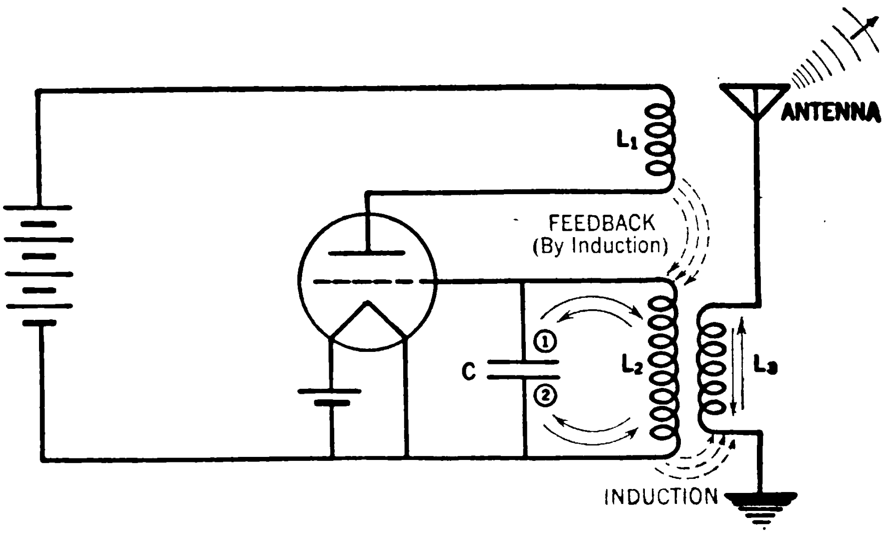
$$\text{voltage gain} = \frac{\text{output voltage}}{\text{signal voltage}}$$

The output voltage is introduced into the next stage for further amplification (or perhaps into headphones or a loudspeaker) by a suitable *coupling* device.

OSCILLATORS

The Triode as a High-Frequency Generator (Oscillator). We shall now see how a triode in combination with a tuned circuit can be made to generate a high-frequency alternating current.

One typical circuit for accomplishing this purpose is shown in the diagram. Its operation is as follows:



An Oscillator Employing Magnetic Feedback Between the Plate and Grid Circuits

1. When the circuit is completed, the plate is positive with respect to the filament. Plate current begins to flow.
2. As plate current flows through coil L_1, a magnetic field builds up and cuts the turns of wire in coil L_2, thus inducing a current in L_2.
3. The current through L_2 is in such a direction as to draw electrons away from the grid and plate 1 of the condenser C and store them on plate 2 of the condenser. Thus the condenser becomes charged and the grid becomes more positive.
4. The positive grid increases the plate current, which in turn strengthens the field around L_1, which induces a stronger current in L_2, which charges the condenser still more and makes the grid more positive, which further increases the plate current—and so on.
5. As a result, the plate current quickly rises to saturation and become steady; therefore the magnetic field around L_1 becomes steady, and the inductive effect on L_2 disappears.
6. The condenser now begins to discharge through L_2, making the grid less positive. This causes the plate current to decrease.

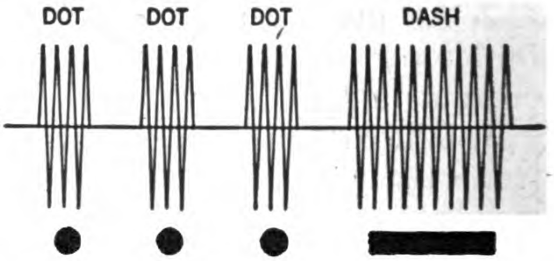
The resulting decrease in the magnetic field around L_1 induces an emf in L_2 which aids the discharge of the condenser, thus making the grid even less positive. This continues until the grid is so negative that plate current is cut off altogether.

7. The condenser has in the meantime become charged in the opposite direction—plate 1 is negative and plate 2 positive. It now begins to discharge once more, causing the grid to become more positive, and the entire cycle repeats.

Thus an oscillating current of high frequency is set up in the L_2C circuit. This LC circuit is called a *tank* circuit. The rate at which the sequence of steps 1 to 7 occurs—in other words, the frequency of oscillation—is the same as the resonant frequency of the tank circuit.

The oscillating current in L_2 induces an rf voltage in L_3, and this voltage causes electrons to surge back and forth between the antenna and ground, thereby causing the emission of a radio wave at the same frequency as the frequency of oscillation in L_2C.

Feedback. The magnetic coupling between L_1 in the plate circuit and L_2 in the grid circuit is called *feedback,* because some of the energy in the plate circuit is "fed back" into the grid circuit. In *positive* feedback, any change in plate current result in a change in grid voltage which acts to *increase* that change; in *negative* feedback, any change in plate current is *opposed* by the corresponding action induced in the grid circuit. Positive feedback is always necessary to produce oscillation.

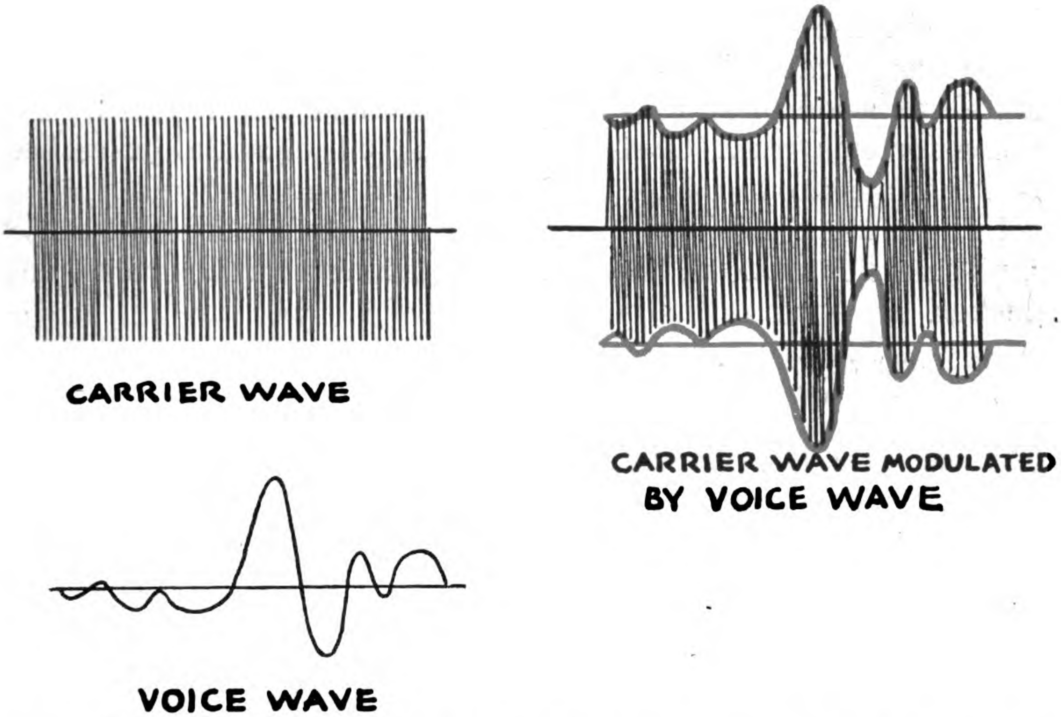


The carrier wave is interrupted to send "dots" and "dashes" in Morse code.

Radio Telegraphy. The radio wave emitted by the oscillator is called a *carrier wave.* The carrier wave can be turned on and off by means of a key inserted in the plate or grid circuit of the oscillator. Thus a series of dots and dashes can be sent out in the form of "pieces" of the carrier, and messages can be sent in code (such as International Morse code). To transmit speech and music, however, the carrier wave must be *modulated,* as described in the next paragraph.

MODULATION

Amplitude Modulation. If the output of a microphone, phonograph pick-up, or similar device is properly connected or coupled to the plate circuit of an oscillator, the sound fluctuations will be superimposed on the radio frequency fluctuations of the plate current. The effect will be to increase and decrease the amplitude of the rf carrier wave in accordance with the variations of the sound or *audio frequency* wave. Thus the carrier wave will have an *envelope* with the same shape as the audio frequency (af) wave, as shown in the diagram. This process is called *amplitude modulation.*



CARRIER WAVE

CARRIER WAVE MODULATED BY VOICE WAVE

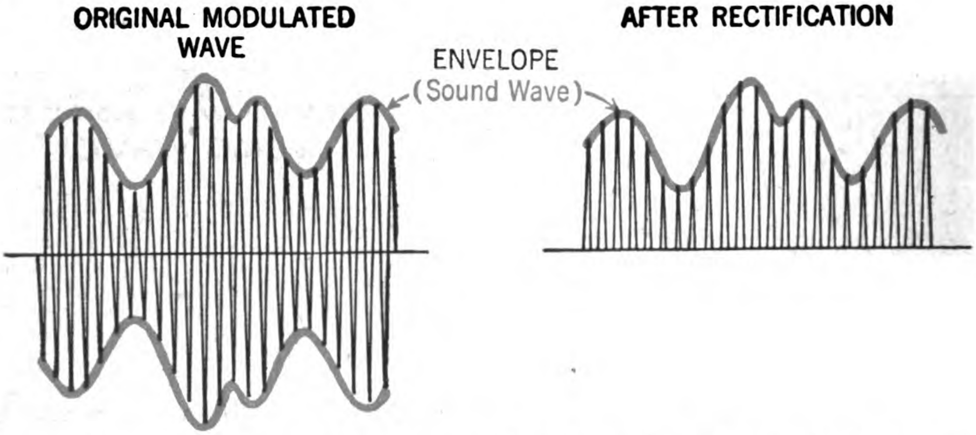
VOICE WAVE

Amplitude Modulation of a Carrier. Note how the voice wave becomes the "envelope" of the carrier. The envelope of the bottom half of the carrier is a mirror image of the envelope of the top half.

Frequency Modulation. The rf carrier wave has two distinguishing features—its amplitude and its frequency. We have seen how the *amplitude* can be modulated to carry audio frequency signals. Practical methods have now been developed for modulating the *frequency* of the carrier, keeping its amplitude constant. This development is largely the work of Major E. H. Armstrong, an outstanding pioneer in radio history.

In frequency modulation (FM) the frequency of the carrier increases and decreases around its average value in step with the audio frequency fluctations. Since the amplitude of the wave is constant, an ordinary receiver designed to respond to AM will give no response to FM—special receivers are necessary to hear FM programs.

FM has certain distinct advantages, chief of which is the virtual elimination of static and other electrical disturbances. The reason for this is that static is an amplitude modulation of the carrier wave produced by radiation from lightning discharges, motor sparks, etc. Since the FM receiver does not respond to amplitude fluctuations, the static noises never reach the loud speaker.

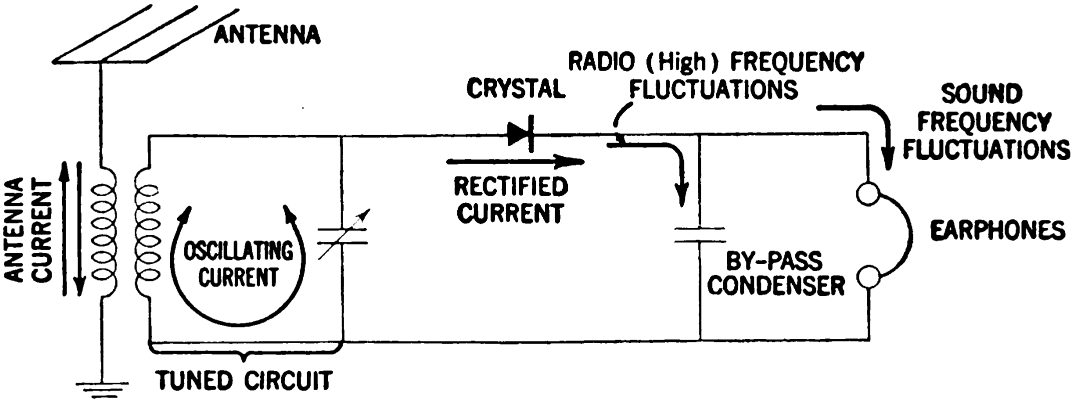


A loud speaker or earphone will respond to the audio frequency envelope of the carrier after rectification.

DETECTION

Detection. Detection is essentially the process of separating the audio frequencies or modulation envelope from the rf carrier in the receiver in order to make headphone or loudspeaker response possible. First, the modulated wave must be rectified; that is, one half must be eliminated so that the wave pulses are all in one direction. Then provision must be made to send the af component through the headphones or speaker and to by-pass the rf component. This discussion will be limited to detectors for AM only; FM detectors operate on entirely different principles.

The crystal detector. A simple crystal detector circuit is shown in the diagram. The incoming modulated signal induces an rf voltage (and electron surge) in the antenna. The antenna current induces an oscillating current in the tuned circuit. The voltage across the tuned circuit tends to drive an oscillating current through the earphones and crystal. But the crystal, usually galena (lead sulfide), acts as a one-way valve for electrons, allowing current to flow through it in only one direction. Thus the crystal rectifies the modulated signal, eliminating the negative half. The output current through the crystal is unidirectional, but varies at an rf rate; the amplitude has the same shape as the modulation envelope and varies at an af rate.

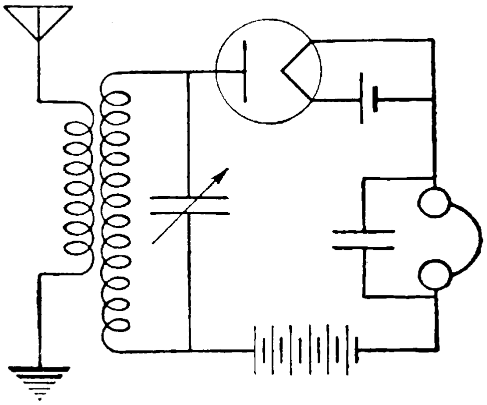


The (Galena) Crystal Receiver

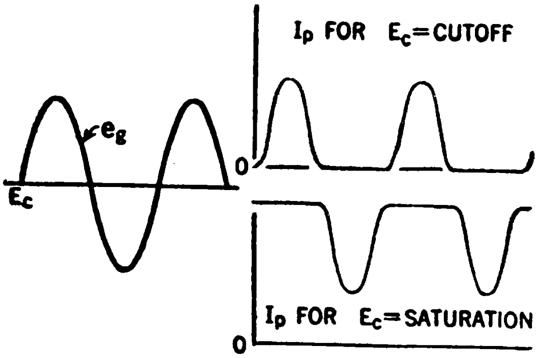
The headphones, having fairly high inductance, would offer a very high impedance to rf currents; therefore the entire current output of the crystal cannot be sent through the headphones without seriously reducing the current strength. This problem is solved by "short-circuiting" the headphones for rf with a "by-pass" condenser of fairly low capacitance. This condenser offers a low impedance path for the rf component of the crystal current, but a high impedance path for the lower frequency af component. As a result, the af component takes the "easier" (lower impedance) path through the headphones, while the rf component takes the path through the condenser (the easier path for it).

The use of fixed condensers to provide separate paths for currents of different frequencies is fundamental to all radio circuits. The most important application of this kind is separating DC (zero frequency) currents from AC currents. Whenever you see a fixed condenser in a circuit diagram, you can be sure it is either separating DC from AC or af from rf currents.

The diode detector. As shown by the diagram, the simple diode detector circuit closely resembles that of the crystal detector. Likewise, the operation is basically the same. Since plate current flows only when the plate is positive, the negative loops of the modulated input are eliminated. The rectified plate current contains rf and af components. The af goes through the headphones and the rf goes through the by-pass condenser. The diode detector is employed in nearly all receivers today because it can rectify larger currents than any other detector with very little distortion.



The Diode Detector



If the grid bias of a triode detector is set for plate current cut-off, plate current flows only on the positive half-cycles of the grid signal voltage. If the bias is set for plate current saturation, the plate current dips during the negative half-cycles of grid signal voltage. In either case, the AC voltage applied to the grid is rectified in the plate circuit.

Triode detectors. Triodes can be used as detectors by operating them biased almost to cutoff. On each positive swing of the signal, a pulse of plate current flows; but the negative swing has practically no effect on plate current because the grid voltage swings below the cutoff bias. The same result can be obtained by operating the tube biased almost to the saturation point, in which case the positive swing of the signal has little effect on the plate current. Triodes used as detectors have the advantage of amplifying the rectified signal, but they do not give as good fidelity as diodes.

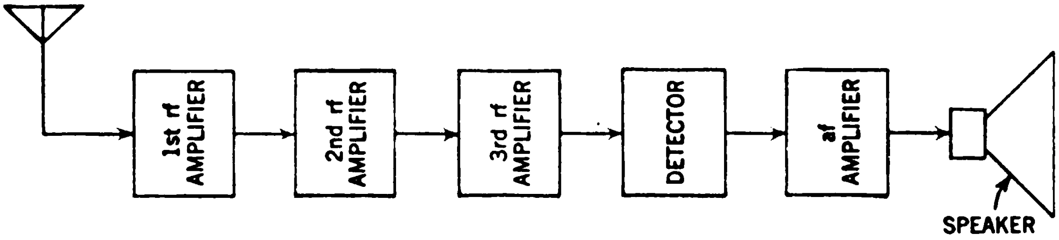
Functions of Vacuum Tubes Summarized. The various functions of vacuum tubes have now been described. They are:

1. *Rectification*—changing AC to DC.
2. *Voltage amplification*—producing an AC voltage across a load impedance which has the same frequency as the input or signal voltage, but which has a greater amplitude.
3. *Oscillation*—generating AC currents and voltages of high frequency.
4. *Detection*—producing an audio frequency signal from a modulated rf radio wave.

RECEIVERS

Radio Receivers. At first glance, circuit diagrams of radio receivers appear hopelessly complicated. Actually, they are fairly simple. They look complicated because many successive operations must be performed on an incoming radio signal, and the whole set of operations is presented in one diagram. If, however, the circuit is broken down into small sections, each performing a single function, the circuit becomes easy to understand. This is what we do when we draw a block diagram of a receiver. Within each block you imagine one of the special circuits which have been described in this chapter. A line connecting one block with another means that the output of the first block becomes the input of the next. A few examples will serve to explain block diagrams.

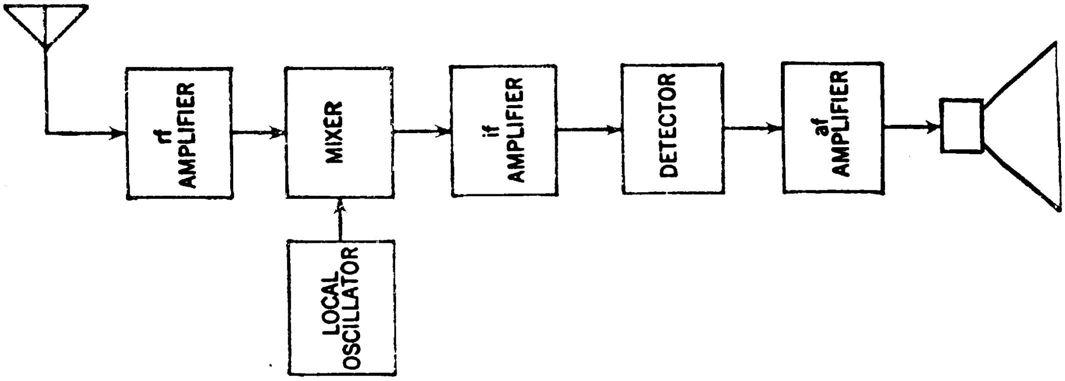
Tuned Radio Frequency Receivers. The block diagram of a 5-tube "trf" receiver follows..



The incoming signal picked up by the antenna is selected by the tuned circuit of the first radio frequency amplifier. The amplified output of this stage is introduced into the tuned circuit of the next stage for further amplification. This is repeated in the third stage. The highly-amplified modulated signal next enters the detector circuit, where the rf and af components are separated. The af is then sufficiently amplified in the next stage to operate the loudspeaker. Note that there are no rf currents anywhere in the last stage.

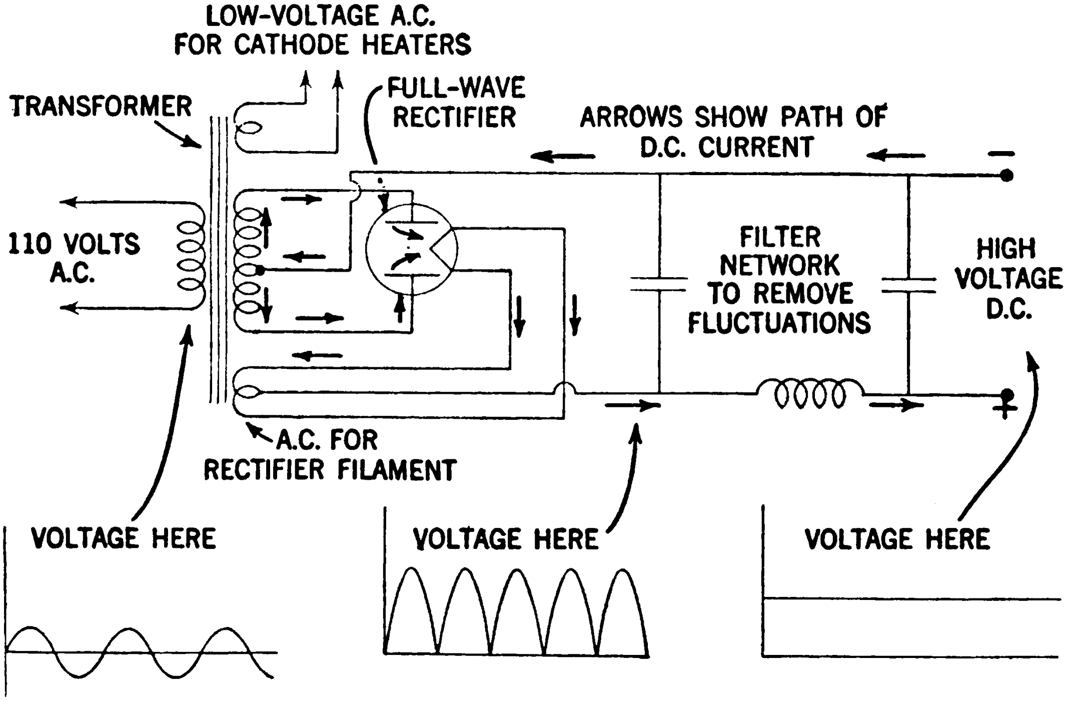
The three rf amplifiers and the detector must all tune accurately to the same frequency. This is accomplished with one tuning dial by mounting the rotating plates of all four identical variable condensers on the same shaft. Trf receivers have good fidelity, but only moderate selectivity and sensitivity.

Superheterodyne Receivers. This type of receiver circuit was designed by Major Armstrong during World War I; it has today replaced nearly all other types of general purpose receivers. The block diagram of a 6-tube superheterodyne receiver follows.



The desired signal frequency is selected by the tuned rf amplifier, and the amplified output is introduced into the *mixer* stage. The mixer combines this rf signal with a radio frequency generated by the *local oscillator.* The oscillator frequency is controlled by a tuning condenser which is varied at the same time the rf amplifier is tuned, and by the same dial. Provision is made so that the frequency of the oscillator is always higher than that of the selected signal by a constant value, usually 465 kilocycles. When these two frequencies are combined in the mixer, a new *intermediate frequency* (if), the difference between them, is produced in accordance with the principle of beats (p. 146). For example, if a signal frequency of 1200 kc is selected, the frequency of the local oscillator will be 1665 kc; hence the intermediate frequency will be 1665 – 1200 kc = 465 kc. The production of a beat frequency in this manner is called *heterodyning,* and is the unique feature of superhet receivers. The 465 kc if output of the mixer (which is still modulated) is amplified in the if stage (a *fixed frequency* amplifier), the output of which goes through the detector and af amplifier to the speaker.

Chief advantages of superheterodyne circuits are high amplification in the if stage, increased selectivity and sensitivity, and good fidelity. In some circuits, the rf amplifier is omitted; the functions of mixer and oscillator may also be performed by a single tube known as a *converter*. The superheterodyne principle is used in FM and television, as well as in AM broadcasting.

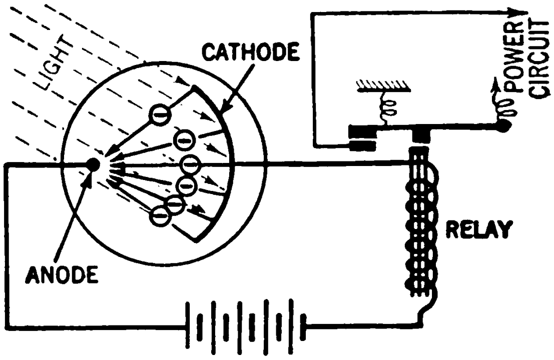


Power Supply for an AC Receiver

Power Supplies for AC Receivers. Since the majority of power circuits in the home supply 110 volts of AC, it is desirable to design radio receivers so that they can be operated directly from such power lines, instead of using batteries. In order to do this, a *power supply* must be incorporated within the receiver which will provide low voltage for the vacuum tube cathode heaters and a high DC voltage for the vacuum tube plates. This is accomplished by means of a transformer with several secondary windings, and a rectifier vacuum tube, connected as shown in the diagram. One winding of the transformer steps up the house voltage to the desired plate voltage. The rectifier tube (a double diode) then changes this AC voltage to DC; since the diode has two plates, and the plates are connected to the transformer in such a way that they are positive alternately, both halves of the AC cycle are rectified. One plate operates during one half, the other plate during the other half of the cycle. The fluctuations in the DC produced are smoothed out by a *filter network* of condensers and inductances.

OTHER APPLICATIONS OF ELECTRONICS

Photoelectric Effect. The *photoelectric cell,* or "electric eye," operates on the fact that certain metals, notably cesium, rubidium, potassium, and selenium, emit electrons when light is directed on their surfaces. This is known as the *photoelectric effect,* and has many applications, especially when used in conjunction with vacuum tube circuits.



When light strikes the cathode, the relay is energized, thus closing a circuit which operates some electrical device.

One type of photoelectric cell is a vacuum tube with a loop of wire at its center maintained at a positive potential. The cell has an inside coating of the sensitive metal at negative potential. When light strikes the cell, the sensitive metal gives off electrons which are attracted to the positive electrode; thus current flows in the circuit. The intensity of this current varies directly with the intensity of the light falling on the sensitive surface.

The feeble current produced by the cell can be made to operate electromagnetic relays which control larger currents that may, in turn, open or close doors, turn on drinking fountains, operate burglar alarms, etc. Photoelectric cells are vital elements in modern sound motion pictures and in television.

Sound Motion Pictures. Modern sound pictures are projected from films upon which the sound as well as the action have been recorded. During production, the sound accompaniment enters a microphone. The weak pulsating current is amplified and made to operate a *light valve,* a slit opening between two metal strips that alternately move closer together and farther apart according to the pulsations of the current. The light valve regulates the amount of light from a lamp that passes through to affect the edge of the film alongside the recording of the action. When the film is developed, the *sound track* shows up as a series of light and dark bands of varying width. The reproduction of the sound portion of such film consists of concentrating light on the sound track and allowing that which gets through to fall upon a photoelectric cell. The resulting pulsating current is introduced into an amplifier which operates a loudspeaker. Here the original sound accompaniment is reproduced.

Television. *Transmission.* The basic idea in television broadcasting is to take the picture being telecast and break it up into a large number of separate spots, like the pieces of a jig-saw puzzle. When the pieces are put together in their proper arrangement at the receiver, the original picture is reconstructed. In the jig-saw puzzle, the pieces are scrambled; in television, the pieces are "cut out" in a definite order, transmitted in that order, and put together in the same order. The process of dividing a picture into a large number of segments, according to some definite scheme, is called *scanning.* In modern television transmitters, scanning is accomplished by a moving electronic beam in a special tube called an *iconoscope.*

In the iconoscope is a screen for receiving the image to be transmitted. This screen is made of mica with a metal plate on one side and perhaps 200,000 tiny light-sensitive globules on the other—really 200,000 tiny photoelectric cells. A cathode emits electrons, and a high-voltage electrode drives them in a beam toward the screen. One pair of electromagnetic coils above and below the electron beam and another pair on either side deflect the beam horizontally and vertically so that it will strike any desired point on the screen.

The image of the scene being televised is focused on the light-sensitive screen by an ordinary lens system. The pattern of light "kicks out" electrons from the globules in proportion to the light intensity at various points. The globules thus become charged positively forming a "charge" image of the scene. By condenser action, the metal plate on the other side of the mica screen becomes charged negatively.

By means of the deflecting coils, the electron beam is now made to move at high speed from one side of the screen to the other in parallel, slanting lines, thus scanning this "charge" image. This beam replaces the electrons lost by the globules; each time it does so, the metal plate on the other side of the screen also discharges. The electrons leaving the charged plate constitute a varying current whose intensity corresponds to the intensity of the light pattern at the various points of the image. This current is amplified and used to modulate an rf carrier. This modulating signal consists of many frequencies, varying from low af to high frequencies of about 4000 kc. This complex signal is called the *video* signal, and corresponds to the audio signal in sound broadcasting.

Reception. The television receiver contains another special vacuum tube, called the *kinescope,* which reproduces the "sight" portion of the broadcast. On the inside of the large end is a fluorescent coating to serve as a screen. A beam of electrons bombards this screen and causes it to glow with an intensity proportional to the intensity of the electron stream, which in turn depends on the video-frequency currents being received. Deflecting coils or plates make the electron beam move across the screen in the same manner as in the iconoscope, and the rate and manner of deflection is synchronized with the transmitter. Thus the image reproduced on the kinescope screen is made to correspond with the image on the screen of the iconoscope.

The reality of television, as with moving pictures, depends on persistence of vision. In television we see a succession of pictures drawn by the lightning strokes of an "electronic pencil." Each part of the screen fluoresces for a short interval after the passage of the beam, so that the image at any one point persists until the next passage of the beam across that point. The electron beam travels across the screen at a rate of about 2 miles per second, constructing as many as 30 complete pictures per second. Thus there is no appreciable flicker on the screen.

X-rays. The X-ray tube is very much like a diode radio tube. It contains a cathode for emitting electrons and an anode to which they flow. It differs, however, in several important ways. The anode is a heavy block of tungsten (called the *target*). The voltage applied to this anode is very high—as much as 50,000 or 100,000 volts in recent models. As a result, the electrons are drawn to the anode with tremendous speeds. When they strike the tungsten, electromagnetic radiations of very short wave length are emitted. These radiations are similar to light waves, but have much greater powers of penetration. Therefore they can be used to take photographs of the interiors of objects, especially where a dense material, such as bone, is hidden by a light material such as flesh. X-rays have also been applied to the detection of flaws in structural metals and machine parts.

The Cathode-Ray Oscillograph. The oscillograph makes use of a tube similar to the television receiver kinescope. The electron beam in this tube is made to trace out the form of any wave which is to be studied, producing an image of the wave on the screen. Wave studies of this kind are important in analyzing and correcting vibrations in propellers, engine parts, etc.

Other Industrial Applications. Thousands of devices for an almost endless list of different purposes have been and are being developed today, all based on applications of the vacuum tube in its several forms—oscillator, photoelectric cell, X-ray tube, amplifier, rectifier, etc. These various uses of vacuum tubes are grouped under the general name of *electronics*. Radio is the best-known application of electronics. Several others have been mentioned in the preceding paragraphs. A few less well known ones are: selecting and controlling the colors of textiles; regulating the position of the paper in two-color printing, so that the red and black in this book, for example, will line up with each other in the proper position; baking or heating the interior of an object without heating the surface; protecting workers from injury by turning off machines when parts of the body come too close; detecting odors which the human nose cannot sense; aiming guns and bombs; and many war applications which are closely guarded secrets.

The International-Morse Code for Radio Telegraph Messages. The following system of dots and dashes has been accepted by all nations as the one to be used in radio telegraph communication. The code is transmitted by means of a key which sends out a musical note when it is depressed and cuts off the sound when it is released. When the key is held down for a very short interval, a "dot" is sent. The "dash" is transmitted by holding the key down three times as long as for a dot. The time between dots and dashes is about the length of a dot. The time between the end of one letter and the beginning of the next in the same word is about 3 dots or 1 dash. For suggestions on how to send the International-Morse code, see the September and October 1941 issues of *QST*, the radio amateurs' official magazine.

In learning to receive or "copy" the code, it is best to think of the code letters in terms of their *sound* rather than their written appearance. For example, think *dit-dit-dit-dah* for the letter V, rather than *dot, dot, dot, dash*. For this purpose it is advisable to have either a receiver on which code signals can be heard, or a code oscillator on which you can practice sending and receiving code messages. Instructions for constructing a simple oscillator which will produce a musical note similar to actual received signals are given on the next page.

INTERNATIONAL MORSE CODE

A	· —	**N**	— ·
B	— · · ·	**O**	— — —
C	— · — ·	**P**	· — — ·
D	— · ·	**Q**	— — · —
E	·	**R**	· — ·
F	· · — ·	**S**	· · ·
G	— — ·	**T**	—
H	· · · ·	**U**	· · —
I	· ·	**V**	· · · —
J	· — — —	**W**	· — —
K	— · —	**X**	— · · —
L	· — · ·	**Y**	— · — —
M	— —	**Z**	— — · ·

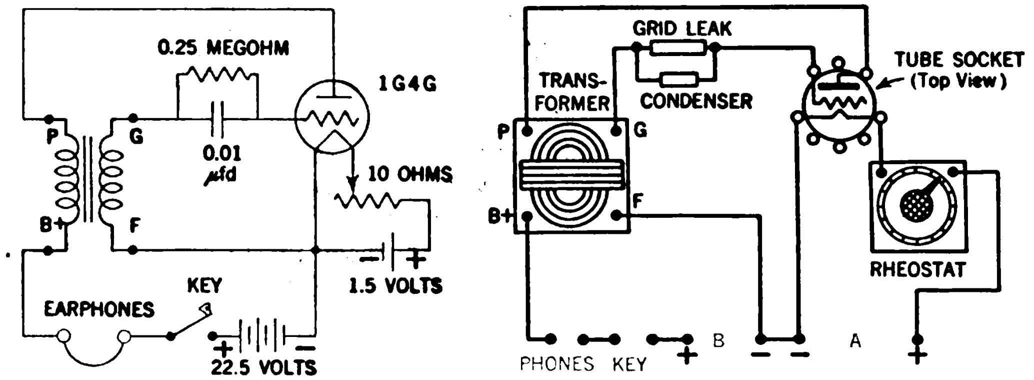
Numerals	
1	· — — — —
2	· · — — —
3	· · · — —
4	· · · · —
5	· · · · ·
6	— · · · ·
7	— — · · ·
8	— — — · ·
9	— — — — ·
0	— — — — —

Other Characters	
Period	· — · — · —
Comma	— — · · — —
Question mark	· · — — · ·
Error	· · · · · · · ·
Wait	· — · · ·
End of message	· — · — ·
Go ahead	— · —
Signing off	· · · — · —

A Simple Audio Oscillator for Code Practice. A reliable and inexpensive oscillator can be constructed with the following parts:

1 tube, type 1G4G
1 octal tube socket
1 old audio transformer
1 grid leak, 0.25 megohm
1 fixed condenser, 0.01 microfarad
1 pair of earphones
1 telegraph key
1 1.5-volt battery (No. 6)
1 22.5-volt B battery
1 rheostat, 10 ohms
wire, baseboard, binding posts, etc.

The schematic wiring diagram and top view of the baseboard are shown below. With all connections made, and the rheostat at minimum resistance, a musical tone should be heard in the earphones when the key is closed. If nothing happens, reverse the connections on either side of the transformer (not both). The pitch can be adjusted by changing the rheostat setting.



The parts named in red in the right-hand diagram are to be connected to the binding posts indicated by the series of black dots.

BEST ANSWER TEST

1. Almost all radio receivers in use today employ (1) storage batteries; (2) diode detectors; (3) crystal detectors; (4) no detectors.

2. Nowadays, most receivers are tuned by means of (1) fixed inductors; (2) fixed condensers; (3) variable condensers; (4) triodes.

3. In a triode, the electron stream flows mostly from (1) plate to grid; (2) grid to cathode; (3) cathode to grid; (4) cathode to tetrode; (5) cathode to plate.

4. The amplifying properties of a triode are due entirely to the effect of (1) the grid on plate current; (2) the plate on grid current; (3) the cathode on plate current; (4) the cathode on grid current; (5) the tuned circuit.

5. Of the following, the one least associated with radio development is (1) Armstrong; (2) Hertz; (3) DeForest; (4) Maxwell; (5) Ohm.

6. A triode could be converted for use as a diode by connecting (1) grid to cathode; (2) grid to plate; (3) cathode to plate; (4) to an AC power supply.

QUESTIONS

1. Turn on a radio receiver and then charge and discharge a Leyden jar, or operate a static machine, while the set is on. Explain the "static" heard on a radio during an electrical storm.

2. Explain by an analogy with resonance in sound what is accomplished by the "tuning" of a radio receiver.

3. How do you account for the fact that a comparatively small change in grid voltage will cause a much larger change in the plate current of an amplifier tube?

4. Explain what happens in the antenna when radio waves fall upon it.

5. Explain how an LC circuit produces a high-frequency oscillating current.

6. What determines the strength of the current that flows in the plate circuit of a photoelectric cell.

7. A radio program is broadcast from an open-air platform in Portland, Maine. Who hears the words and music first, (*a*) a listener 200 feet from the platform in Portland, Maine, or (*b*) a listener at his radio receiver in Portland, Oregon, 3000 miles distant? (Air temperature is 30°C.) **Ans. (b)**

8. An amateur radio transmitter is operated from a 120-volt, 60-cycle house circuit. (*a*) The heater of one vacuum tube operates at 10 volts. Draw a fully-labeled diagram of a transformer that will provide this voltage. (*b*) The plate of another tube operates at 480 volts. Draw a fully-labeled diagram of a transformer that will provide this voltage. (*c*) Could one transformer provide both of the required voltages? Explain. (*d*) The plates of most vacuum tubes require DC voltage. Name one device that will furnish this DC from the AC source. (*e*) The filament of the vacuum tube in (*a*) has a resistance of 2 ohms. Calculate its power consumption. (*f*) If the filament transformer is 80% efficient, what current does the operating filament draw from the house circuit?

APPENDIX

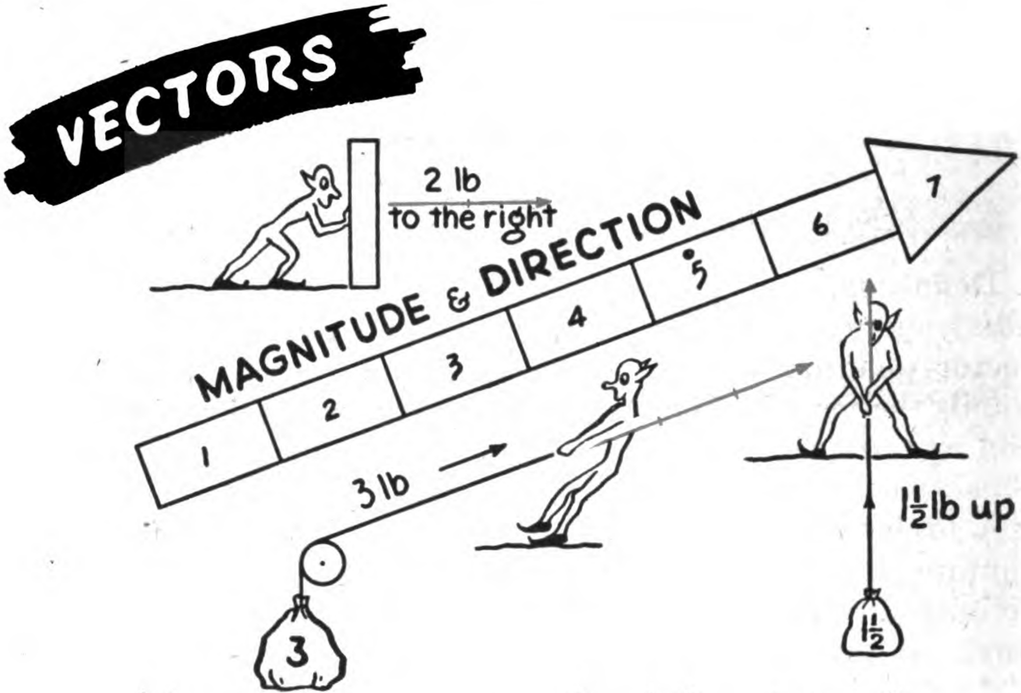
VECTORS

Definition. Any quantity which has a definite size (or *magnitude*) and a definite *direction*, is called a *vector quantity*. Such a vector quantity can be represented by an arrow whose length equals the magnitude of the quantity (to some convenient scale), and whose direction corresponds to the direction of the quantity. This arrow is called a *vector*.

A force is a typical vector quantity, because every force has a definite magnitude (so many pounds or grams) and acts in a definite direction. Therefore, forces may be represented by vectors.

Applications of Vectors. As we shall see, vectors can be used to analyze the effects of forces. They are also useful for calculating the effects of velocities in different directions, such as the case of an airplane flying in one direction with a wind blowing in another direction. In electricity, the most important application of vectors occurs in the analysis of alternating current circuits. It has been found that an AC current or voltage can be represented by a vector which is assumed to be rotating about its tail. By means of such vectors, and the laws of vector addition illustrated in this section, AC voltages or currents may be added, even though such voltages or currents are changing in value from moment to moment. This use of vectors is illustrated in Chapter 9.

Vector Representation of Forces. A force may be represented by a vector drawn to scale (say, 1 in = 80 lb) with an arrowhead at one end to show the direction. The tail of the vector would be the point at which the force is acting. If several forces are acting at the same point, their vectors would all have a common tail point. Such forces are called *concurrent*.



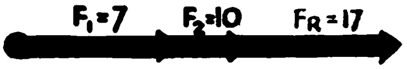
The vector representation of each force is in red.

Resultant of Concurrent Forces. The *resultant* of two or more forces acting simultaneously upon the same point of a body is the single force which would produce the same effect if it replaced all the original forces. The determination of the resultant of concurrent forces is termed the *composition* (addition) of forces.

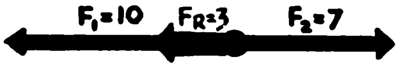
Two Forces in the Same Direction. *The resultant of two concurrent forces in the same direction (0° apart) is their arithmetical sum.* The resultant of 10 lb and 7 lb acting in the same direction is 17 lb; that is, a force of 17 lb will produce the same effect as the two forces combined. (See diagrams, next page.)

Two Forces in Opposite Directions. *The resultant of two concurrent forces in opposite directions (180° apart) is their arithmetical difference, and its direction is in the direction of the greater force.* The resultant of 10 lb to the left and 7 lb to the right is a force of 3 lb to the left; that is, a single force of 3 lb to the left would produce the same effect as forces of 10 lb to the left and 7 lb to the right combined.

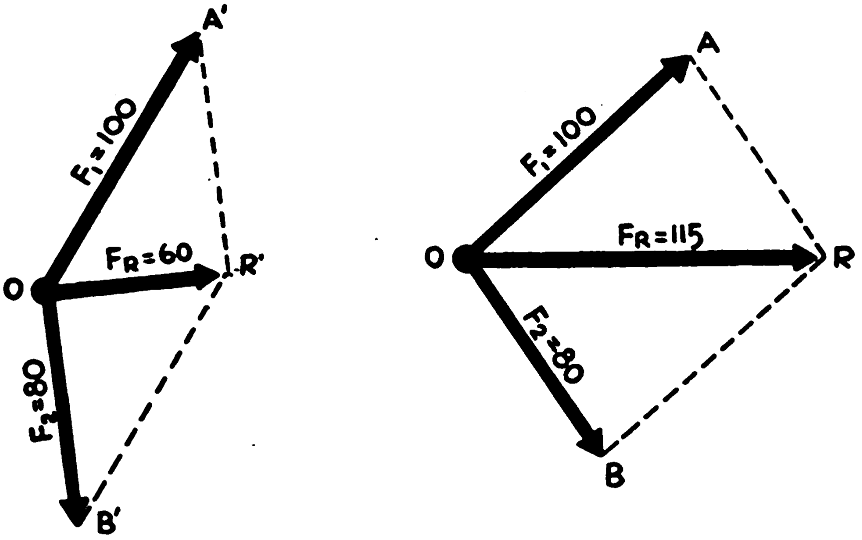
Two Forces at an Angle. *The resultant of two concurrent forces acting at an angle between 0° and 180° is represented by the diagonal of a parallelogram drawn to scale with the two forces at the given angle as the sides.*



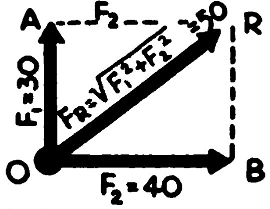
SAME DIRECTION



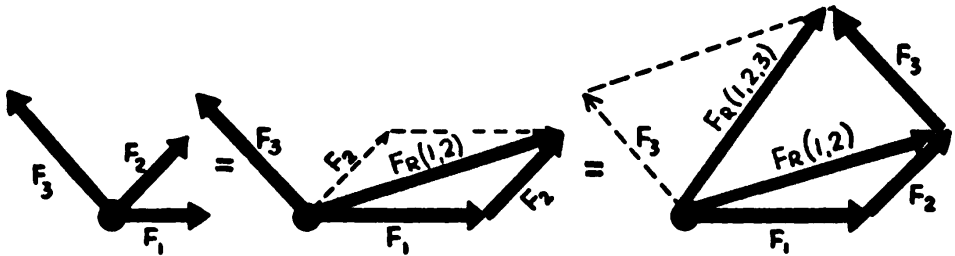
OPPOSITE DIRECTIONS



AT ANY ANGLE



AT RIGHT ANGLES



SEVERAL CONCURRENT FORCES

Let OA and OB represent two forces, 100 lb and 80 lb respectively, drawn to scale and at a given angle. Complete the parallelogram, $OARB$, and construct the diagonal, OR, which represents both the magnitude and the direction of the resultant of OA and OB. The value of OR may be determined by measurement, and in this case is equal to 115 lb; that is, a single force of 115 lb in the direction OR will have the same effect as the combined forces of 80 lb and 100 lb in the directions OA and OB respectively. Note that the resultant of two forces may be less than either of them (parallelogram $OA'R'B'$).

Two Forces at Right Angles. *In the case of two concurrent forces at right angles, the resultant is the square root of the sum of the squares of the two forces. That is, the resultant force* (F_R) may be computed by the Pythagoras theorem, giving a more rapid and more accurate result.

$$F_R = \sqrt{F_1^2 + F_2^2}$$

Resultant of Several Forces. Any set of concurrent forces, no matter how many, may always be represented by a single resultant force. The method is illustrated in the bottom diagram on page 179. As shown, first find the resultant of two of the forces by the parallelogram law; in the diagram, $F_R(1, 2)$ is the resultant of F_1 and F_2. Then find the resultant of this force and one of the remaining forces; $F_R(1, 2, 3)$ is the resultant of $F_R(1, 2)$ and F_3. This procedure is continued until all the forces have been used.

As the diagram shows, the same result may be obtained by the *polygon method*: add the vectors head to tail, maintaining the proper direction of each. The resultant is the vector drawn from the tail of the first vector to the head of the last, thus forming a polygon.

When the forces themselves form a closed polygon, the last vector ending at the tail of the first, there is no resultant—the forces are in equilibrium.

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OUTLINE OF TOPICS [*]

I. Magnetism (*Chap. 1*)

- A. Natural magnet (1)[**]
  - 1. Lodestone
- B. Artificial magnets (1)
  - 1. Temporary, soft iron
  - 2. Permanent, steel
  - 3. Magnet shapes
- C. Polarity and law of magnetic attraction (1–2)
  - 1. The north-seeking pole is the north pole of a magnet
  - 2. Like poles repel
  - 3. Unlike poles attract
- D. Magnetic fields (2–3)
  - 1. Lines of force are closed curves extending from north to south poles
  - 2. Lines of force do not cross
  - 3. Lines of force concentrate where the magnetic field is most intense
- E. The earth's magnetic field (6)
  - 1. The earth is a magnet
  - 2. The earth's magnetic poles do not coincide with the geographic poles
- F. The compass (6–9)
  - 1. The compass points in a direction which is parallel to lines of force
  - 2. Magnetic deviation
  - 3. Magnetic variation
  - 4. Magnetic dip
- G. Magnetic induction (5–6)
  - 1. Inducing magnetism by contact
  - 2. Inducing magnetism by stroking
- H. Theory of magnetism (4–5)
  - 1. Molecules of a magnetic material are themselves magnets
- I. Magnetic materials (5–6)
  - 1. Permeability
  - 2. Retentivity
  - 3. Reluctance

II. Electrostatics (*Chap. 2*)

Work in the field of electrostatics is aimed at providing background for understandings which are developed in later units. Most important of the understandings which this unit should develop are those concerned with the electron theory. Therefore, constant reference should be made wherever possible to the electron theory as a means of explaining phenomena.

- A. Structure of matter (12–13)
  - 1. Protons
  - 2. Electrons
- B. Electron theory (13–14)
- C. Nature of positive and negative charges (10–12)
  - 1. Difference between a magnetic field and a static charge
  - 2. Law of electrostatic attraction
- D. Charging (13–18)
  - 1. By contact
  - 2. By induction
- E. The condenser (18–25)
  - 1. Leyden jar
  - 2. Tinfoil condenser
- F. Electric discharge (25–28)
  - 1. Discharge from point and sphere
  - 2. Lightning
  - 3. Use of lightning rod
- G. Concept of electric current as a flow of electrons (14, 19)
  - 1. Conductors
  - 2. Insulators

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[*] Taken from War Department publication PIT-101, *Fundamentals of Electricity, A Basic Course.*

[**] Numbers in parentheses refer to pages in this book.

III. Primary Cells (*Chap. 3,* pp. 30–33)

- A. Voltaic cell theory (copper, zinc, ammonium chloride)
  - 1. Ionization of electrolyte
  - 2. Zinc becomes zinc chloride and accumulates a negative charge
  - 3. When the external circuit is complete, the electrons leave the zinc and flow to the carbon
  - 4. The NH_4+ ion receives the electron and hydrogen is liberated
  - 5. Polarization
    - *a.* The depolarizer
  - 6. Local action
    - *a.* Amalgamation
- B. Current designation
  - 1. Electrons flow from − to +
  - 2. The current flows from + to −
- C. Two dissimilar metals in an electrolyte may produce electric current
- D. The dry cell
  - 1. Construction
  - 2. Action
  - 3. Possible causes of failure
    - *a.* Zinc eaten away
    - *b.* Loss of water
    - *c.* Polarization

IV. The Storage Battery (*Chap. 3,* pp. 33–40)

- A. Electrolysis of water (33–35)
  - 1. Ion difference in electrolyte and nonconducting liquid
  - 2. Liberation of hydrogen and oxygen at electrodes
- B. The lead cell (36–38)
  - 1. Charging
  - 2. Discharging
- C. The commercial lead storage battery (38–39)
  - 1. Construction
    - *a.* Plates
    - *b.* Electrolyte
    - *c.* Separators
    - *d.* Case
    - *e.* Arrangement within battery
- D. Testing and care of lead cell (39–40)
  - 1. The hydrometer
  - 2. Polarity on charging
  - 3. Possible troubles
    - *a.* Buckled plates, clogged or broken separators, etc.
    - *b.* Sulphation
    - *c.* Electrolyte impurities

V. Voltage, Current, Resistance (*Chap. 4*)

- A. Electricity as a flow of electrons (42)
- B. Amperage (44)
  - 1. The ampere as the number of electrons passing a given point on a wire in a given time
  - 2. Relative amounts of current
- C. Voltage (44–45)
  - 1. The volt as the "push" behind electrons
  - 2. Relative voltage
- D. Resistance (45)
  - 1. The ohm as a measure of the resistance to the flow of electrons
- E. The resistance of a conductor depends on (45–46)
  - 1. Length
  - 2. Cross section
  - 3. Material
  - 4. Temperature
- F. Ohm's law—$I = \frac{E}{R}$ (46)
- G. Circuits (46–54)
  - 1. Resistances in series
  - 2. Resistances in parallel
  - 3. Simple series-parallel circuits
- H. The thermostat (55–56)
- I. Factors determining current and voltage produced by a cell (56–57)
  - 1. Size of plate
  - 2. Internal resistance (neglect in all computations)
  - 3. Materials

- J. Battery connections (57–60)
  - 1. Series
  - 2. Parallel
  - 3. Simple series-parallel connections
  - 4. Meaning of "short circuit"

VI. Electromagnetism (*Chap.* 5)

- A. Oersted's experiment (63–65)
  - 1. Field about a current-bearing conductor
- B. Strength of field depends on (65)
  - 1. Current
  - 2. Number of turns
  - 3. Material of core
- C. The polarity of a solenoid (64)
  - 1. Right-hand electromagnet rule
- D. The relay (66–67)
- E. The circuit breaker (67–68)
- F. The telegraph (66–67)
- G. The electric bell (65–66)

VII. Meters (*Chap.* 5, pp. 68–74)

- A. Principle of meter movements (68–69)
  - 1. Moving coil
  - 2. Plunger vane
- B. The galvanometer (69)
- C. The ammeter (69–70)
  - 1. A galvanometer with a low resistance shunt in parallel
- D. The voltmeter (70–71)
  - 1. A galvanometer with a high resistance in series
- E. Circuit use of meters (71–74)
  - 1. Ammeter as series instrument
  - 2. Voltmeter as parallel instrument
  - 3. Ammeter-voltmeter method of measuring resistance

VIII. Heating Effects of Electric Current (*Chap.* 6, pp. 84–88)

- A. A current flowing through a wire produces (84)
  - 1. A magnetic field
  - 2. Heat
- B. Heating effect (85)
  - 1. In series circuits
  - 2. In parallel circuits
- C. Fuses (87)
- D. The hot wire ammeter (87–88)
- E. The incandescent lamp (86–87)
- F. The arc (88)

IX. Work, Energy, and Power (*Chap.* 6, pp. 75–84)

- A. Force (75)
  - 1. A "push" or "pull"
  - 2. Unit of measurement—Pound
- B. Work (75–77)
  - 1. A force exerted through a distance, overcoming a resistance
  - 2. Unit of measurement—Foot-pound
- C. Energy (78–79)
  - 1. The ability to do work
  - 2. Types of energy
    - *a.* Mechanical
    - *b.* Heat
    - *c.* Light
    - *d.* Chemical
    - *e.* Electrical
  - 3. Conversion of energy from one form to another (particularly to electricity)
- D. Power (79–81)
  - 1. The rate of doing work
  - 2. Units of measurement
- E. The watt as the electrical unit of power = (EI) (81–82)
- F. The wattmeter (82)
- G. The watt-hour as the electrical unit of work = (EIt) (83–84)
- H. Resistance losses in heat are directly proportional to: (84–85)
  - 1. The resistance
  - 2. The square of the current
  - 3. The time

X. Induced Electromotive Force (*Chap. 7*, pp. 91–100)

- A. Faraday's experiment (91–93)
  - 1. Whenever a conductor cuts a line of force, an induced electromotive force (EMF) causes a current to flow in the conductor
  - 2. Direction of induced current
  - 3. Lenz's law
  - 4. The strength of an induced EMF varies as
    - *a.* Field strength
    - *b.* Speed of motion
    - *c.* Number of turns of wire
- B. The a-c generator (93–97)
  - 1. Parts and operation
    - *a.* The field magnet
    - *b.* The armature (bipolar)
    - *c.* The slip rings and brushes
- C. The nature of alternating current (*Chap. 9*)
  - 1. Electron picture
  - 2. Cycle and frequency
  - 3. Interpretation of a rotating vector in graph form
  - 4. Alternating current across condenser
  - 5. Direct current across condenser
- D. The d-c generator (93–95, 97–99)
  - 1. Parts and operation
    - *a.* The field magnet
    - *b.* The armature
    - *c.* The commutator and brushes
  - 2. Series type
  - 3. Shunt type (emphasize)
- E. Bipolar and multipolar generators (99–100)

XI. Motors (*Chap. 7*, pp. 100–105)

- A. Relation of d-c generator to motor (100)
  - 1. In terms of energy conversion
  - 2. Similarity of construction
- B. Force acting on a current-bearing conductor in a magnetic field (100–101)
  - 1. Left-hand rule
- C. The d-c motor (101–104)
  - 1. Series
  - 2. Shunt
  - 3. Bipolar and multipolar
  - 4. Back EMF
  - 5. Applications

XII. Mutual and Self-Induction (*Chap. 8*)

- A. A current flowing in one circuit may induce a current in a nearby circuit if the flux is varying (107–108)
- B. The induction coil (112–114)
  - 1. Parts and operation
    - *a.* Primary
    - *b.* Secondary
    - *c.* Condenser
  - 2. The automobile ignition system
- C. The transformer (109–112)
  - 1. Step-up
  - 2. Step-down
  - 3. Energy relations
- D. The telephone (114–115)
  - 1. Transmitter
  - 2. Receiver
  - 3. Circuit
- E. Self-induction (108–109)
  - 1. Impedance
  - 2. Inductance and capacitance in series (briefly)

XIII. Rectification of Current (*Chap. 9*, pp. 129–130; *Chap. 11*, 154–157)

- A. Converter (motor-generator) (129)
- B. Copper oxide rectifier (129–130)
- C. Vacuum tube (154–157)
  - 1. Edison effect
  - 2. Diode tube

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